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Wave-induced pressures in porous bonded revetments. Part II: Pore pressure just beneath the revetment and in the embankment subsoil

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ABSTRACT

This paper considers pore pressure distribution in the embankment subsoil beneath PBA-revetments, based on the results of the parameter study using the new validated CFD–CSD model system *wavePoreGeoFoam* described in the companion paper (Part I), which focusses on wave-induced pressures on PBA-revetments (Alcérreca-Huerta and Oumeraci, 2016-in this issue). In this paper (Part II), a general overview is first provided on the numerical parameter study, especially on the model setup for the extraction of data related to the wave-induced pore pressures in the sand core beneath PBA-revetments. Secondly, wave-induced pore pressure just beneath the revetment is analysed considering: peak pressure magnitude, its location beneath the revetment and their spatial distribution. Afterwards, a process analysis of the results of the parameter study is performed for the wave-induced pore pressure distribution in the sand core. Formulae are developed for the prediction of the pore pressure distribution just beneath the revetment and of the damping of peak pore-pressures in the sand core. Subsequently, a comparative analysis of the proposed formulae and the approach of De Groot et al. (2006) for the assessment of pore pressure in a porous seabed is made, showing a very good agreement between both results. Finally, implications and recommendations for engineering applications and for further research are drawn from the results.

1. Introduction

Highly porous polyurethane bonded aggregate (PBA) revetments are a novel alternative which reduce the wave-induced loads on and beneath the revetment compared to conventional revetments. However, the hydro-geotechnical processes involved in the interaction of waves with PBA-revetments and their foundations must be better understood in order to improve the design of these revetments and to avoid failures or collapsing of the structure due to soil liquefaction or excessive deformations of the embankment subsoil.

Wave-induced flows and transient pore pressures have been investigated analytically and numerically for long waves on permeable sea beds (Liu et al., 2007) and for sea bed response under waves and around marine structures (De Groot et al., 2006; Jeng et al., 2013; Liu and García, 2006, 2007; Zhang et al., 2011, 2012). In Liu et al. (2007), analytical solutions were used to verify the accuracy of their numerical solutions, which combine the Navier–Stokes equations for wave motion together with the exact two dimensional diffusion equation for seepage flow. Integrated models (e.g. PORO-WSSI II) have been developed for the analysis of wave-permeable structure-porous seabed interactions. These models are based on the Volume-Averaged/Reynolds-Averaged Navier–Stokes (VARANS equations) and Biot's poro-elastic theory (Jeng et al., 2013; Liu and García, 2006; Zhang et al., 2011, 2012). Furthermore, physically based analyses are described in De Groot et al. (2006) regarding wave-induced pressures and liquefaction around marine structures.

Though wave-induced pressures on exposed seabeds have been analysed, the applicability of the formulae proposed for covered porous seabeds such as the sand embankment beneath PBA-revetments had not yet been examined.

Therefore, the companion paper (Alcérreca-Huerta and Oumeraci, 2016-in this issue) investigated the wave-induced pressures on the revetment, based on the results of a parameter study using the validated CFD–CSD (computational fluid dynamics–computational solid dynamics) model system *wavePoreGeoFoam*. A brief introduction to the CFD–CSD model, the numerical model setup and the test programme of the parameter study were given and the peak pressure, its location and the pressure distribution on top of the PBA-revetment were analysed.

The focus of this paper (Part II) is on the wave-induced pore pressures, which develop just beneath the revetment and in the sand embankment beneath PBA-revetments as a result of the transfer of the wave-induced pressure on the revetment, treated in the companion paper Part I (Alcérreca-Huerta and Oumeraci, 2016-in this issue). Previous studies, based on large-scale model tests (Oumeraci et al., 2010, 2012) and small-scale laboratory tests (Liebisch et al., 2014, Liebisch, 2015), were conducted for this purpose. However, due to time and

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cost restrictions as well as further practical constraints in the laboratory, the range of conditions to be tested and the number of transducers deployed (e.g. pressure sensors) were limited. To overcome these limitations, a comprehensive study is performed and which is reported in this paper with a focus on the pore pressure in the sand core beneath PBA-revetments.

First, a general overview of the numerical parameter study is presented (further details are described in companion paper Part I and Alcérreca-Huerta and Oumeraci, 2014). Second, the wave-induced peak pressure, its location and pressure distribution just beneath the revetment (on top of the sand core) are analysed and the formulae for their prediction are proposed. A preliminary examination of the data from the numerical parameter study is described in order to determine the most appropriate approach for the process analysis. The wave-induced pore pressure damping in the sand embankment is then analysed. As a result of the analyses, a formula is proposed for the prediction of wave-induced peak pressure in the sand embankment beneath a PBA-revetment. The proposed formulae developed in this study for PBA-revetments are compared to the approach of De Groot et al. (2006) for the assessment of pore pressure in unprotected porous seabeds.

Finally, in the concluding section, implications and recommendations for engineering applications as well as for further research are tentatively drawn from the results.

2. Numerical model: Description, setup and parameter study

A brief description of the numerical model (*wavePoreGeoFoam*) and the model setup used in the parameter study is made in this section. Further details are described in Part I (Alcérreca-Huerta and Oumeraci, 2016-in this issue) and in Alcérreca-Huerta and Oumeraci (2014).

The CFD–CSD model wavePoreGeoFoam is a 3-dimensional model developed in OpenFOAM. The CFD code solves the VARANS equations and considers wave generation/absorption based on the "relaxation zones" technique of the toolbox *waves2Foam*, developed by Jacobsen et al. (2012). On the other hand, Biot's fully dynamic equations coupled with Darcy's law were implemented in the CSD solver. The one-way coupling of the solvers takes place at the porous–nonporous boundaries.

The numerical tests are preformed only for regular waves tests, including five wave periods (T = 3.0, 4.0, 5.0, 7.0 & 9.0 s) three wave heights (H = 0.3, 0.6 and 1.0 m) and a water depth h = 4.0 m. The regular waves are generated according to the wave theory that best fit to the combination of wave conditions and water depth set in the simulations, i.e. Stokes II and Stokes V wave theories. The k-ε model with the inclusion of the closure term for porous media has been implemented for the simulations. Five revetment slopes are considered (cotα = 1.5, 2.0, 3.0, 4.0 & 6.0) and three revetment-filter thicknesses d_{rev} = 0.15 m, 0.25 m and 0.35 m are investigated. The test programme consists of a total of 135 tests with surf similarity parameters ranging from $0.62 < \xi_0 < 13.28$.

The model setup considered a similar configuration to that of the GWK tests (Oumeraci et al., 2010) with wave generation at x = 0 m, the start of a 1:20 sandy slope at x = 220 m and the revetment toe beginning at x = 240 m. The mesh for the CFD simulations included 400,000–500,000 cells (ranging between 0.02 m and 0.05 m) to simulate the full domain, whilst the mesh for the CSD simulations considered ~20,000–30,000 cells (ranging between 0.02 m and 0.10 m) to model the revetment, the filter layer and the embankment subsoil (s. Fig. 1).

The empirical parameters defined for the CFD numerical simulations (namely porosity n, coefficients α_f and β_f for the Darcy–Forchheimer equation according to Engelund, 1953 and D_{50}) and for the CSD model (permeability K, and D_{50}) are shown in the table embedded in Fig. 2. Furthermore, virtual pressure transducers (VPTs) are placed in the sand core as well as on and beneath the porous bonded revetment. In the sand embankment, four layers of VPTs were set at different depths with a spacing of 0.20 m for the first three layers and 0.40 m between the third and fourth layer. The model setup and the number of VPTs are shown in Fig. 2, for a 1:3 slope and a revetment-filter thickness d_{rev} = 0.35 m.

3. Wave induced pressures on top of the sand core beneath the revetment

In the numerical parameter study, the wave-induced pore pressures on top of the sand core beneath the revetment are investigated. The results of the analysis and the development of prediction formulae are presented for: i) the wave-induced peak pressure, ii) its location on top of the sand core of PBA-revetments and iii) the pore pressure distribution along the slope of the sand embankment. The peak pressure on top of the sand core is denoted as p_{max3}, in order to differentiate it from the peak pressure on the revetment p_{max1} (as used in Part I). Peak pressure p_{max3} represents the maximum value of the dynamic pore pressure obtained in each test with 10–20 regular waves.

Two main wave loading cases are distinguished in this study (see also companion paper Part I): i) impact loads, normally induced by plunging breakers ($0.8 < \xi_0 < 2.4$) and described by a pressure peak of short duration (impact component) superimposed on a quasi-static component (related to the cyclic wave motion); and ii) non-impact loads, usually generated by surging and collapsing breakers ($\xi_0 > 3.3$), are caused by the cyclic wave motion (also considered as quasi-static loads).

3.1. Peak pressure on top of the sand core

The results from the numerical simulations are compared to the results from the large-scale tests in GWK (Oumeraci et al., 2010) in Fig. 3. When comparing the relative peak pressure on top of the revetment and the peak pressure on top of the sand core (Fig. 3), non-impact loads as well as the quasi-static component of impact loads are only slightly damped through the revetment and filter layers. This dissipation is small, even for the largest revetment-filter thickness considered.

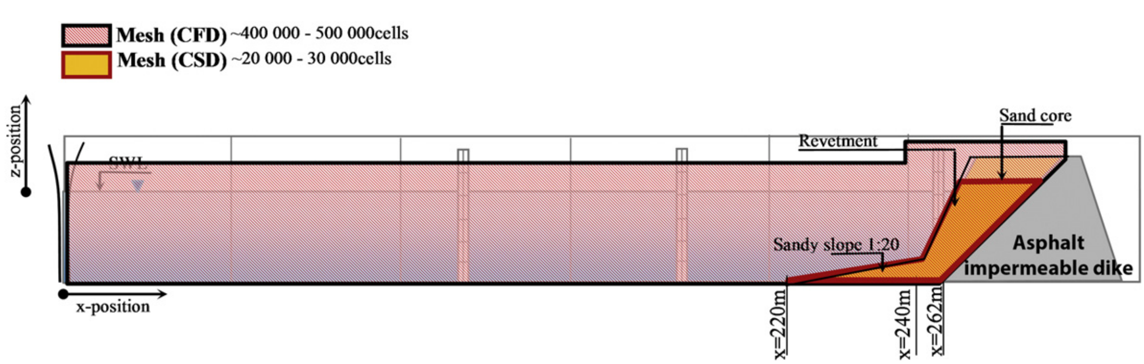

Fig. 1. Model setup in GWK tests and meshes generated for the CFD–CSD model.