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DRAINS INFLUENCE ON THE BEACH GROUNDWATER HYDRODYNAMICS

Piera FISCHIONE, Daniele CELLI, Davide PASQUALI & Marcello DI RISIO

Università dell'Aquila, Dipartimento di Ingegneria Civile, Edile, Architettura e Ambientale,Laboratorio di Idraulica Ambientale e Marittima (LIam), P.le Pontieri, Monteluco di Roio, 67100, L'Aquila, Italy.
Corresponding author: piera.fischione@graduate.univaq.it

EXTENDED ABSTRACT

La spiaggia è un sistema dinamico che risente in maniera diretta di un'alterazione del suo equilibrio morfodinamico. Poiché sulla costa si concentra una sempre più crescente presenza di attività antropiche ed economiche, essa rappresenta un'area estremamente sensibile e vulnerabile. Le azioni di contrasto e di gestione dell'erosione possono inserirsi quindi nei piani di gestione a scala regionale finalizzati ad aumentare la resilienza di quelle realtà la cui stabilità risulta provata da squilibri del bilancio dei sedimenti. Se da una parte le opere rigide di protezione costiera sono efficaci in un'ottica di mitigazione del fenomeno, dall'atra esse non incidono direttamente sul bilancio negativo di materiale sedimentario che abbandona la fascia attiva. I metodi di intervento non rigido, sebbene più sostenibili da un punto di vista ambientale, hanno carattere temporaneo e incorrono in maggiori costi di gestione e programmazione. Il drenaggio costiero si configura come un sistema non strutturale di stabilizzazione della linea di riva che, da solo o accoppiato ad altri sistemi, può essere utile per la mitigazione dell'erosione costiera nell'ambito di un approccio sostenibile da un punto di vista ambientale.

Facendo riferimento alla fisica propria dei mezzi porosi, il drenaggio costiero (Beach Drainage System, BDS) basa il suo funzionamento sull'interazione tra la falda e le onde frangenti rispetto al trasporto solido trasversale. Costituito da una serie di dreni orizzontali installati all'interno della spiaggia (a cui consegue un impatto visivo nullo) parallelamente alla costa, il suo effetto è quello di deprimere la superficie di saturazione nel mezzo poroso rendendo la sabbia non satura e favorendo l'infiltrazione. La perdita di energia potenziale così ottenuta fa diminuire il potere erosivo del moto ondoso. Il funzionamento del BDS è governato da una serie di parametri che possono influenzarne la funzionalità. Nonostante la teorizzazione del suo funzionamento e sperimentazioni in tutto il mondo iniziate da diversi decenni, ad oggi ancora non è chiara l'efficacia del sistema. Non esistono, infatti, linee guida né criteri di progettazione universalmente riconosciuti dalla comunità scientifica nazionale ed internazionale. La conoscenza della risposta della falda in presenza di un dreno è quindi funzionale a capirne il ruolo rispetto alla mobilitazione delle particelle solide di sedimento. Questo studio, che si prefigge di indagare con un approccio numerico il comportamento della falda, è quindi propedeutico all'ottimizzazione del BDS, necessaria alla definizione delle configurazioni di progetto, in relazione alla forzante ondosa e alle caratteristiche del sedimento, che ne esaltino l'efficacia.

Si è fatto ricorso all'uso di un modello di fluidodinamica computazione in grado di risolvere le equazioni di Navier-Stokes per fluidi reali in presenza di onde e nei mezzi porosi, modellati con un approccio tipico della dinamica del continuo, tralasciando il comportamento alla scala del poro. È da sottolineare che in questo studio non è stata presa in considerazione la componente morfodinamica. Inoltre, l'attenzione è focalizzata sull'applicabilità della modellazione numerica del mezzo poroso e dell'effetto del BDS, trascurando l'analisi idrodinamica di dettaglio delle caratteristiche del deflusso all'interno del dreno. Il modello numerico, in grado di riprodurre lo smorzamento all'interno della spiaggia delle oscillazioni della falda forzate dalle onde incidenti, è stato applicato a tre casi differenti: dapprima è stato analizzato l'effetto del dreno in assenza di forzante esterna (onde); poi è stato analizzato l'effetto delle onde in condizioni non drenate (assenza di dreno) e, infine, il caso di spiaggia drenata sotto l'azione delle onde. L'analisi dei risultati ha rivelato che, per il caso drenato, la dimensione caratteristica del dreno (cioè il diametro) influisce sull'entità dell'abbassamento della falda e sulla portata esitata. D'altra parte, è possibile osservare che le oscillazioni della falda nel mezzo poroso in caso di drenaggio non sono influenzate sensibilmente dal diametro del dreno, ma lo è solo il livello medio.

ABSTRACT

The aim of this paper is to investigate the role in the groundwater level dynamics played by drains of a Beach Drainage System (BDS) with different nominal diameters.Three different cases are considered: drained beach without incoming waves; undrained beach with incoming waves, and drained beach with incoming waves. Hence, a preliminary numerical investigation on the hydrodynamics inside a sandy beach is carried out, accounting for the presence of both short water waves and a BDS. The (Volume Averaged) Reynolds Averaged Navier Stokes (RANS) equations are solved by using the Finite Volume Method, and the Volume of Fluid (VOF) is used to track the groundwater table fluctuations by using an OpenFoam® solver. To represent the draining surface, the atmospheric pressure at the drain boundary is imposed. In order to reproduce the concentrated head losses, a low permeability layer around the drain is used. The model is able to catch the damped behaviour of the water table oscillation inside the sandy porous medium forced by the incoming short waves. In case of drained beaches, the drain dimensions play an important role in the outflow velocities at the boundary of the pipe. On the other hand, the drain diameter does not affect the general behaviour of the groundwater level inside the beach, but within an area close to the drain location.

Keywords*: beach drainage, coastal groundwater dynamics, fine porous medium, numerical modelling.*

INTRODUCTION

In order to avoid losses and damages in coastal areas, i.e. in order to act on the probability of flooding or erosion and its negative effects on the environment, human health, cultural heritage and economic activities (e.g., Damiani *et alii*, 2018), it is central to assess coastal risk (e.g. Di Risio *et alii*, 2017) and to set strategies (e.g., Airoldi *et alii*, 2005) within the frame of effective coastal zone management. If on one hand, hard structures often cause a shift of erosion process along neighbouring areas, soft solutions were demonstrated to be long-term unsustainable (e.g., Saponieri *et alii*, 2018a) due to their temporary nature (e.g., Pilkey & Cooper, 2012). In order to limit the drawbacks of both, soft engineering methods are frequently combined with coastal structures (e.g., Di Risio *et alii*, 2010; Saponieri *et alii*, 2018a; Saponieri *et alii*, 2018b).

Beach Drainage System (hereinafter referred to as BDS) can be seen as a soft method aimed to achieve shoreline stabilization and to lengthen nourishments life cycle. Basically, the groundwater level is lowered so that the dry sand stability is improved. The system functioning relies on the presence of buried drain(s) laid parallel to the shoreline. The obtained lowered groundwater table induces the decrease of velocities during uprush and back-swash, with respect to the undrained condition. Then the sediment deposition during the runup is enhanced and transport during the rundown is limited. The selection of the BDS configuration is still a challenging topic in coastal engineering and management. Its efficiency has not been recognized as fully working (e.g., Turner & Leatherman, 1997) because of the controversial performances exhibited during the years (e.g., Ciavola *et alii*, 2008; Bain *et alii*, 2016). Both field and laboratory experiences on the system response show that the effective beach stabilization is still not well addressed (e.g., Mariani & Turner, 2013, Contestabile *et alii*, 2013).

The interaction between water table, incoming waves and morphodynamic effects denotes the complexity of the problem, i.e. many aspects have to be considered to gain positive performances of the tools. The outcomes are influenced by several factors, i.e. sand characteristics (Horn *et alii,* 2008), wave energy conditions, pipes characteristics, hydraulic regime inside the drains (Damiani *et alii*, 2011), and number of drains (Ciavola *et alii*, 2013).

To provide criteria for the design of effective BDSs, it is important to understand which the optimum configuration is. This paper deals with the numerical modelling of the effects of the system. The main purpose is to investigate the evolution of groundwater levels, and then the drain influence upon the water table elevation. In the study illustrated herein, the water table response to the incoming waves is evaluated by means of a Computational Fluid Dynamics (hereinafter referred to as CFD) tool, that accounts for the water flow into both the porous medium and water phase, wave generation and active absorption.

The focus here is on the hydrodynamic aspects: no morphodynamic effects are analyzed, i.e. only the resulting water table dynamics affected by short waves and BDS is considered. The analysis refers to the cases of different positions and diameters of the drains.

The comparative analysis let state whatever is the influence of the drain in terms of waves oscillation damping within the sandy beach. Further insight on the influence of the BDS parameters on the water table elevation can be useful to assess its reliability, also from a morphodynamic point of view, even if not considered in this study.

NUMERICAL MODEL AND BOUNDARY CONDITIONS

The swash zone phenomena represent a challenging source of studies and investigations for researchers (e.g., Gourlay, 1992). Since the inner surf and swash zone are characterized by the interaction of different complex phenomena (i.e. run up and backswash, waves setup, groundwater level oscillations, tidal excursion), its detailed knowledge is important in order to model the short term shoreline position, that is a direct result

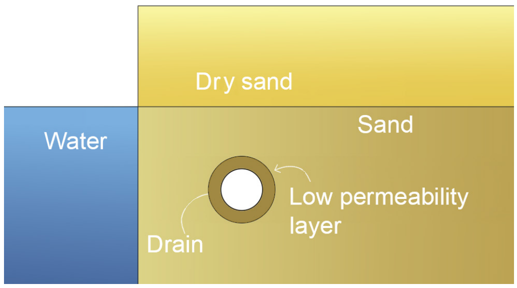

Fig. 1 - Sketch of the drain setup inside the porous medium (sand). The azure shaded area represents the fluid phase. The drain is modelled as a hole surrounded by a low permeability layer (dark brown shaded area).

of cross-shore sediment transport processes (Horn, 2002), in which swash and groundwater table play a role. In this paper, the presence of drains interacting with the swash zone is numerically investigated. The nature of the problem makes necessary detailed flow field information in a confined area. Then, the use of a CFD tool is required to catch the features of groundwater dynamics in the swash zone in the presence of short waves. Previous numerical works have used different simplified approaches, i.e. coupling wave propagation models and geological model or solving simplified equations (Vesterby, 2000; Karambas, 2013; Li & Barry, 2002; Saponieri & Damiani, 2015). The CFD, on the other hand, with its capability to handle equations in their exact form (Wendt, 2008), even if numerically approximated, is reasonably the most accurate method to deal with the problem at hand. Bakhatar (2011) uses Reynold Averaged Navier-Stokes equations only for the hydrodynamics model, coupled with a groundwater flow model. The investigation presented herein takes into account the hydrodynamic behaviour inside an idealized sandy beach by means of a solver, developed within the OpenFoam® framework, capable to compute coastal hydrodynamics by active wave generation and absorption (Higuera *et alii*, 2013), and flow through a porous medium (Higuera *et alii*, 2014). The model relies on VARANS and Darcy's law, i.e. the motion inside the sand is supposed to be laminar (Gu, 1991). Within the frame of VARANS approach, the quadratic term and the inertial coefficient are neglected, the porous medium is considered as a continuum two-phase domain, in which the free surface is tracked by VOF algorithm. The groundwater flow model, though, does not take into account the capillarity fringe, and the medium is considered completely saturated.

The drain is modelled as a hole in the two-dimensional mesh, thus, the dynamics inside the drain is not calculated at all. At the boundary of the drain the atmospheric pressure is imposed. The velocity field is calculated from the pressure. In order to simulate the head losses in correspondence of the draining surface, a lower permeability layer around the drain is considered and modelled (Fig. 1).

NUMERICAL SETUP AND RESULTS

The performed 2D simulations aim to investigate the effects of the drain on the groundwater level in both the (initial) calm water case and the presence of the waves. So, three different steps are necessary to have a general picture of the phenomena. Firstly, simulations without incoming waves are carried out, then only the sandy beach with short waves, and eventually the complete case with waves and drain is simulated. Their setup and results are shown in the following. It is important to stress the comparative nature of the performed analyses: they do intend to highlight the differences between the different configurations for each case.

No waves case

At first, the numerical simulations without incoming waves are carried out. The aim is to investigate the behaviour of the groundwater table inside the sand accounting only for the influence of drain diameters considering an ideal geometry. It is applied in order not to account for the slope beach influence on the comparison amongst the different cases. Figure 2 depicts the numerical setup. The sand body is vertical, 3.5 m high and 10 m wide. The mean water depth is 3 m for all the tests. Drain diameters f equal to 100 mm, 150 mm and 200 mm are modelled all at the same position, with the centre at a height of 2.25 m away from the bottom.

The low permeability filter placed around the drain is 10 cm thick for all the configurations. The filter layer is numerically applied in order to reproduce head losses occurring due to flow expansion when water enters the drain, not directly modelled. Thus, it has not physical meanings. For the given initial water depth, the larger the drain diameter, the lower the initial hydraulic head at the upper point of the drain. The porous medium has been modelled as a fine sand with a mean diameter d_{50} = 0.4 mm, while in the low permeability filter a finer sand whose diameter is d_{50} = 0.2 mm. The porosity is constant and equal to n = 0.4. The value is selected as a typical value according to the literature (see for instance Kovac's, 1981). The atmospheric pressure boundary condition is applied only at the upper half part of the drain in order to describe a drain characterized only by an upper draining

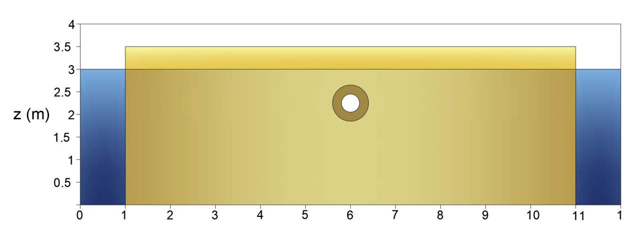

Fig. 2 - Initial condition for the cases without waves. The dark brown shaded area represents the "filter" layer, the lighter brown area is the wet sand. The water table separates the saturated zone from the dry one. The blue area is the clear water.

surface. Then, a no slip wall boundary condition was imposed in the lower part. Velocity is imposed accordingly. Fig. 3 shows a detail of the drain boundary condition for the diameter φ of 200 mm at a given instant.

The velocity field at the drain boundary shows a symmetrical distribution. Its magnitude reaches the maximum at the boundaries of the mid horizontal section, where the velocity is almost twice the one at the top of the drain. It means the water flows more from the sides than from the top. The hydraulic head distribution (higher at the sides than at the top) explains this behaviour.

By a straightforward integration across the draining contour, the outflow discharge per unit length has been obtained. Its trend over time for each of the considered diameter is depicted in Fig. 4.

The global trend for the three configurations is quite constant, and the discrepancy between the φ = 100 mm and φ = 150 mm case is much greater (more than twice) than the one between φ = 150 mm and φ = 200 mm.

A similar behaviour can be seen also in Fig. 5, that shows the groundwater dynamics at a point located at $x = 6$ m (corresponding to the symmetrical axis of the domain).

The groundwater level drop due to the φ= 100 mm drain is greater than the one estimated for the other two (i.e. φ = 150 mm and φ = 200 mm); nonetheless, the drain whose diameter is φ = 150 mm is more efficient than the φ = 200 mm in terms of water table lowering. It can be observed that the higher the drain diameter, the higher the draining surface extension and then the better the hydraulic efficiency of the drain. On the other hand, the higher the diameter, the lower the hydraulic head at the top of the drain and then the worse the hydraulic efficiency of the drain. Then, the φ = 150 mm is a trade-off of the two effects.

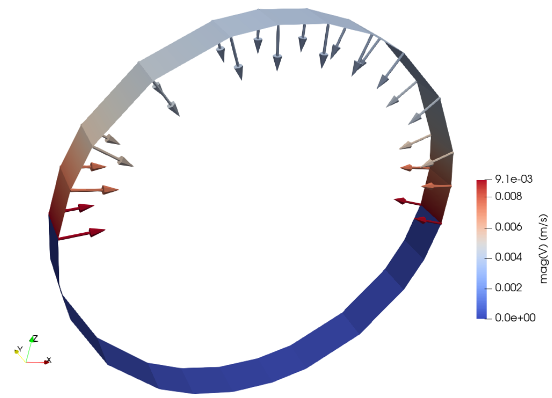

Fig. 3 - Detail of the drain boundary condition for the instant t = 60 s. At the lower part of the drain a no slip wall boundary condition is imposed, resulting in zero velocities. The higher velocities are in the outer upper part.

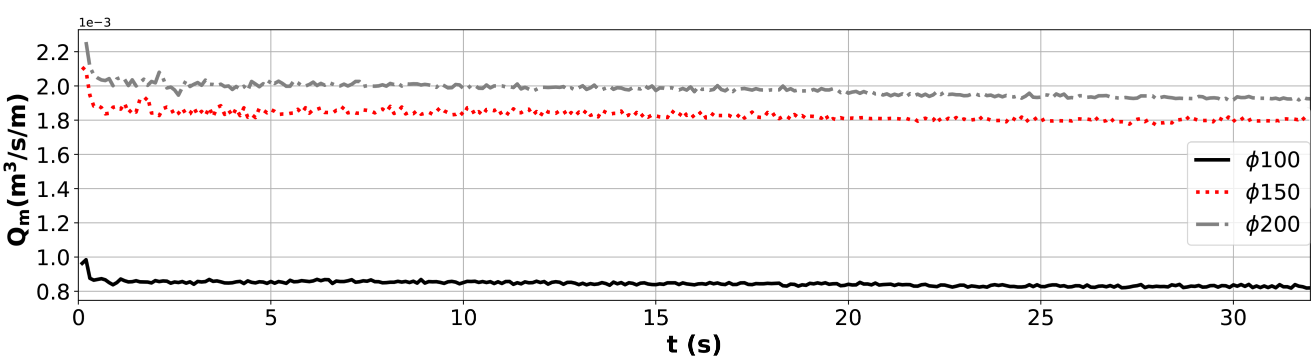

Fig. 4 - Averaged discharge through the draining boundary. The values refer for longshore unit length.

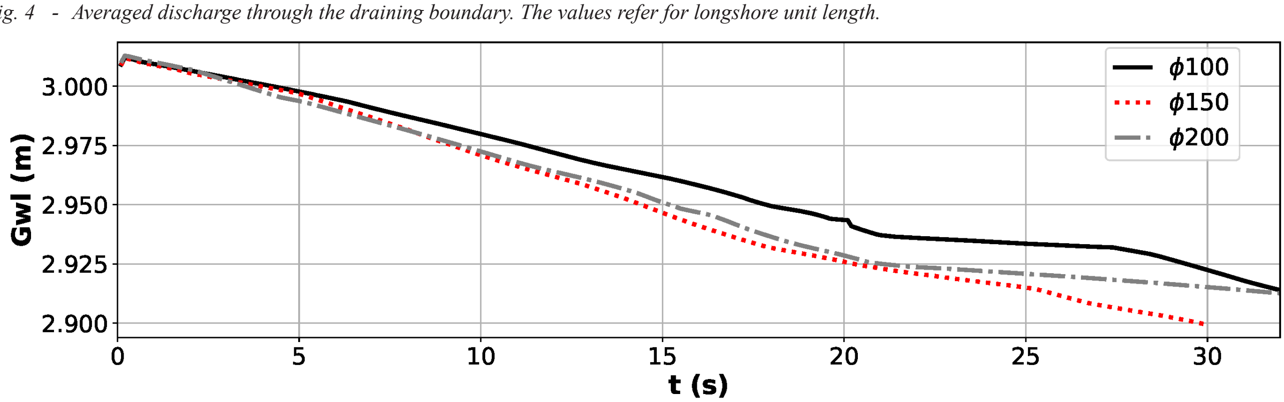

Fig. 5 - Timeseries of the groundwater level at x = 6 m for the different diameters.

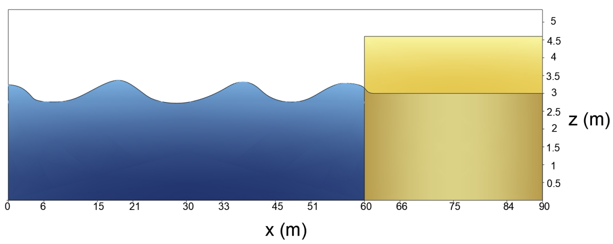

Fig. 6 - Sketch of the numerical domain for the undrained case, in presence of waves.

Undrained case

In this case, no drain has been considered, so only a configuration is tested. The sandy domain is modelled with the same characteristics of the case *No wave* (d_{50} = 0.4 mm, n = 0.4, ideal configuration). The waves propagation is reproduced by using a wider domain: a numerical wave flume 90 m long and 5 m high with a mean water depth h = 3 m. The beach, whose face is placed at 60 m from the offshore boundary, is 4.6 m high. The generated regular waves are characterized by a period T = 5 s and a height H = 1m. The waves characteristics are selected so that the ratio of the wave length and the flume length is maintained at around 4. The wave period is intended to be representative of low energy sea state (i.e. frequent conditions). The wave height has been selected in order to reproduce a low wave steepness (i.e $H/L \approx 0.04$). The Fig. 6 represents a sketch of the computational domain, with a distorted scale to represent the whole numerical wave flume.

The water table oscillations are analysed by means of the standard zero crossing and spectral analyses. Fig. 7 illustrates the mean groundwater oscillations of the individual waves propagating inside the sand and their periods respectively.

The locations of the gauges are indicated in the legend. The beach offshore boundary is located at x = 60 m, so the first numerical gauge is deployed 10 m seaward the offshore boundary

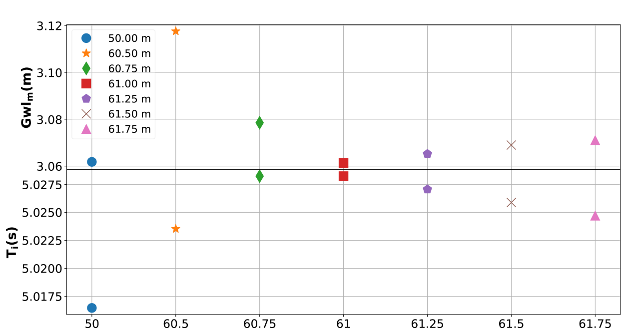

Fig. 7 - Results of zero crossing analysis. Upper panel shows the mean groundwater level for different location inside the beach. Lower panel shows the individual waves periods.

of the beach. The variation of the mean period is small, while an increase in the groundwater mean level can be noticed. The same considerations spring from the Fig. 8, that shows the envelope of the oscillations landward from the offshore boundary of the beach.

The damped behaviour is consistent with the results obtained by means of analytical models of the water waves propagation inside a porous medium (e.g., Nielsen, 1990; Fischione *et alii*, 2019). The raising of the water table with respect to the initial condition is about 10 cm. The spectral analysis is summarized in Fig. 9. The upper panel shows the energy density spectrum, while in the middle panel the amplitude spectrum is shown. Both are estimated in different locations inside the sand. Once again, they reveal that the propagating waves change their amplitude. Lower panel shows a summary of the above observations by means of the coefficient transmission K_t estimated with respect to the water levels recorded offshore the beach (at x = 50 m). The gauges positions are specified in Fig. 9.

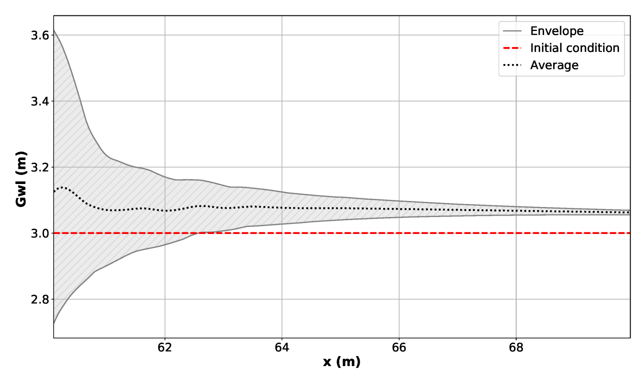

Fig. 8 - Envelope of the groundwater level in space.

Waves and drain

The previous case is here replicated in presence of the drain. The geometrical, physical and hydrodynamic setup are the same of the aforementioned simulations. In this case two drain diameters are considered (φ = 150 mm and φ = 300 mm). The selection of the diameter of 150 mm is due to comparison purposes with the "no waves case", the largest one is considered to test the role of the drain diameter for a wider range of investigation. They are placed at x = 62 m (2 m within the beach with respect to the offshore boundary of the ideal beach) at the same level. Fig. 10 shows the comparison of the groundwater level trend at different locations and for both the drains. While at a certain distance away the drain location (> 1 m) the water table dynamics is not influenced by the diameter of the pipe. As the distance from the drain decreases the larger the pipe diameter, the larger the water table drop (it can be noticed also by the mean level depicted by dashed line). The mean drop in water level is to relate mainly to the draining surface position shift due to the different diameter.

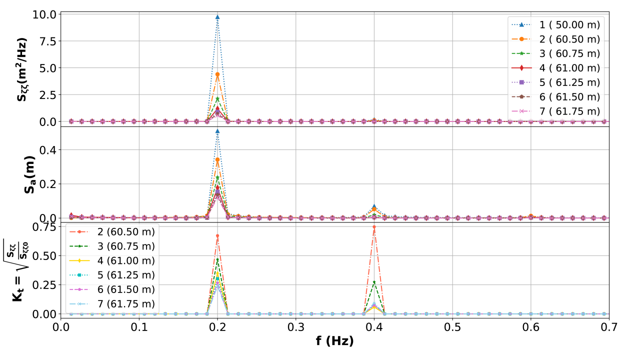

Fig. 9 - Results of spectral analysis. energy density (upper panel) and amplitude spectrum (middle panel). Lower panel shows the transmission coefficient, estimated for all the gauges inside the sand respect to the one located at x=50 m.

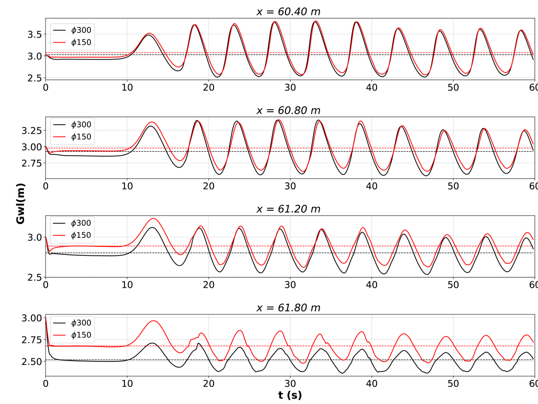

Fig. 10 - Comparison of the groundwater level for different locations inside the beach and for two different diameters. Dashed lines represent the mean value.

In fact, as showed in Fig. 11, the pure water table oscillations, i.e. depurated from the mean level, experience the same damping for both the drains wherever in the domain.

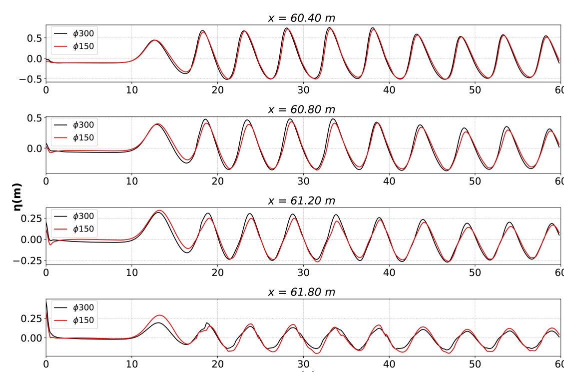

Fig. 11 - Comparison of the groundwater level depurated from the mean value for different locations inside the beach and for two different diameters.

CONCLUDING REMARKS

A numerical model has been used to reproduce the hydrodynamics inside a porous medium, in presence of wave forcing and draining boundary conditions. In order to have insight on the role played by a drain inside a sandy beach, different cases were investigated. To not account for the effect of the slope beach in water table dynamics, an ideal beach with vertical boundaries has been considered. In the simplest case without wave action, three different drain diameters were considered. The obtained differences in discharge and water table dynamics between the smallest diameter (100 mm) and the medium one (150 mm) have resulted to be much greater than the one between the medium diameter (150 mm) and the largest one (200 mm). Considering incoming waves, both the undrained and drained case sare simulated. For the undrained case, while groundwater oscillations are damped by the porous medium, the groundwater mean level does not experience spatial variations.

The presence of the drain, though, affects the dropping of the mean water table in an area close to the drain itself, not depending on the drain diameter to a great extent. It is observed that the model is able to catch the damping behaviour of the wave amplitude inside the porous media.

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