EXPERIMENTAL STUDY OF THE WAVE-INDUCED GROUNDWATER DYNAMICS UNDER DIFFERENT PERIODS

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INTRODUCTION

Coastal beach is alternately covered by and exposed to external driving forces such as waves and tides, leading to significant response in the groundwater dynamics in coastal aquifer, which is closely related to various nearshore issues, e.g., pollutant transport and coastal erosion. A number of recent studies has been conducted to investigate the wave-induced groundwater dynamics (Yang et al., 2022; Zheng et al., 2023). However, the effect of wave periods on the coastal groundwater response is still unclear. In this study, a series of regular wave laboratory experiments were conducted to reveal the spatiotemporal features of the groundwater dynamics including the total water head and the seepage flow, paying particular attention to the wave period effect.

EXPERIMENTAL SETUP

Laboratory experiments were conducted in a 35 m long, 0.8 m height and 0.6 m wide, glass-side wave flume at Zhejiang University (Fig. 1a). A piston-type wave maker was installed at one end of the flume. The initial water depth was set as 30 cm. Regular waves with the same incident wave height of 5 cm while three different wave periods (5 s, 10 s, and 20 s) were adopted in this study to investigate the wave period effect. A 1:10 slope sand beach with medium sand size of 0.356 mm was deployed 14 m downstream of the wave maker. Based on the pre-test, it is confirmed that the capillary fringe height of the experiment sand is 20 cm. In the experiment, the runup heights of all experiments under different wave periods were smaller than the capillary height, indicating that the entire wave-induced swash process occurred within the saturated beach area (under the capillary height). Here, the initial shoreline is assumed to be the datum of the coordinate system with the horizontal landward and vertical upward direction being the positive x and z axis respectively. Incident wave profile was measured at 1 m offshore of the beach toe. As shown in Fig. 1b, pore pressures at z=-5 cm inside the beach were measured using pressure transducer array (HCSC-16, Beijing Heng Rui Chang Tai Technology Co. Ltd) deployed from x=10 cm and extended landward with a spatial interval of 20 cm till x=290 cm.

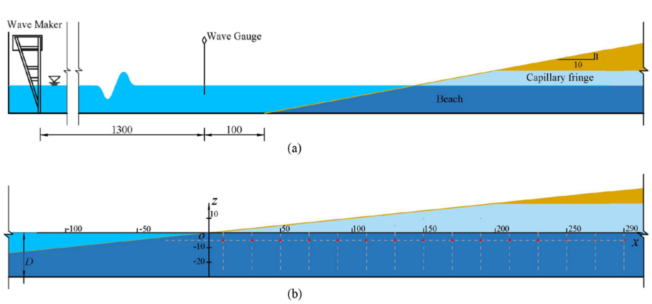

Fig. 1. Schematic diagram of the experimental setup. (a) Side view of the wave flume; (b) Deployment of the pore pressure measuring points (red dots). All dimensions are in cm .

In this study, the total head is calculated as the sum of the position head and the measured pore pressure head. The instantaneous groundwater table elevation at the measuring points was estimated from the local total head based on the hydrostatic assumption (Heiss et al., 2014). Meanwhile, the horizontal hydraulic gradients (corresponding to the local horizontal seepage flow) between two neighboring pressure measuring points are obtained from the measured pore pressures.

RESULTS AND DISCUSSIONS

Regarding the general groundwater flow pattern, different from the solitary wave induced scenario (Yang et al., 2022), it presents varying characteristics under different wave period conditions. Here, dynamic characteristics of the groundwater table is first estimated, followed by the analyses of time-averaged and instantaneous horizontal hydraulic gradient.

Regarding the time history of the local groundwater table, it is found that during the entire wave period, the groundwater table mound (deemed as the boundary between the seaward and landward seepage flows) moves within a limited cross-shore range between x=55 cm and 90 cm when the wave period is 5 s as shown in Fig. 2, resulting in permanent offshore seepage flows in the area seaward of x = 55 cm and onshore seepage flows in the area landward of x = 90 cm. Meanwhile, seepage flow direction in the middle area (between x=55 cm and 85 cm) varies alternately. The movement of groundwater mound extends to a wider range in between x=10 cm and 90 cm under the 10 s period wave condition. Accordingly, the aforementioned permanent offshore seepage flow in the seaward area under 5 s condition could not be observed under the 10 s case, while the permanent onshore seepage flow in the landward area shifts further landward. Similar observation could also be confirmed for the 20 s wave period condition. In addition, it is found that during the entire backwash process of 20 s case, the instantaneous groundwater table is always inclined seaward, resulting in a continuous seaward seepage flow within the measured area. This however could not be observed in the backwash of 5 s and 10 s cases, for which both seaward and landward seepage flows co-exists in the measured area. As for the movement of groundwater table mound, it is related to the instantaneous shoreline during the uprush process, while controlled by the exist point movement during the backwash process. For the short wave period case, there is no time for matured formation of seepage face in backwash, the groundwater table mound thus remains in the vicinity of the maximum runup height. Nevertheless, significant retreat of the exit point during the backwash under the long wave period condition leads to more seaward extension of the groundwater table mount, thus stretching its range as aforementioned.

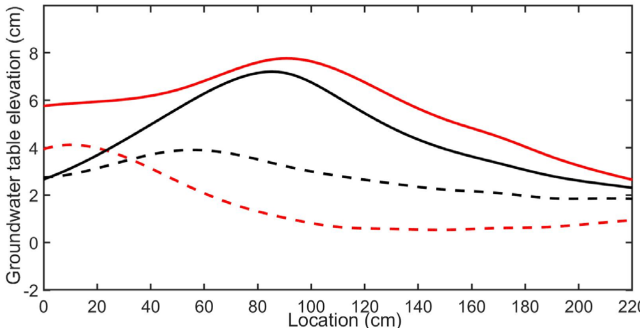

Fig. 2. Groundwater table elevation under 5 s (black) and 10 s (red) conditions. The dashed/solid line represents the most seaward/landward groundwater table mound situation.

Fig. 3 shows the spatial distribution of the time-averaged horizontal hydraulic gradient (representing the local horizontal seepage flow) under different wave period conditions. As the wave period increases, the zero hydraulic gradient position standing for the boundary between landward and seaward seepage flows gradually moved offshore. Meanwhile, the magnitude of the hydraulic gradient (no matter landward or seaward) decreases with the increase of the wave periods. This is related to multiple factors, such as the range of the shoreline movement and the existing time of the seepage face which results in a local elevated total water head and acts as the boundary between seaward and landward seepage flows.

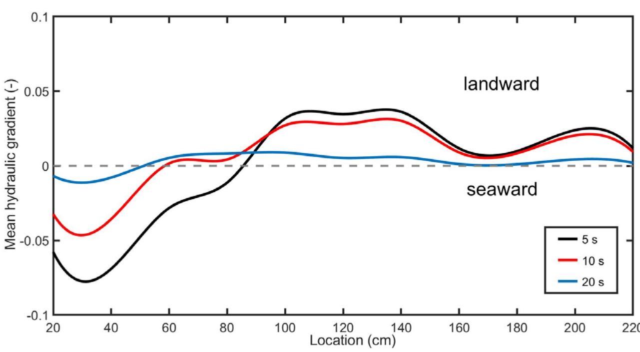

Fig. 3. Spatial distribution of the time-averaged horizontal hydraulic gradient under different wave period conditions.

The instantaneous horizontal hydraulic gradient at different cross-shore positions was also investigated to reveal different hydrodynamic features under different period conditions. Two cross-shore regions could be identified, i.e., Region I corresponding to the area seaward of the uprush limit and Region II located landward of Region I. Here, x=40 cm and x=160 cm are selected as two representative positions of these two regions, whose horizontal hydraulic gradients were examined. Time series of the corresponding results are shown in Fig. 4. As shown in Fig. 4a, horizontal gradient in Region I varies complexly under the influence of various mechanisms, e.g., meniscus mechanism and the effect of seepage face (Zheng et al., 2022). The horizontal gradient under 5 s period condition is smaller than zero during the entire wave period, indicating a permanent seaward seepage flow in Region I. As the wave period increases, landward seepage occurs in this region. Furthermore, the horizontal gradient keeps close to zero for a while (around the dimensionless time 0.6) when the wave period is 20 s, indicating that there is almost no horizontal seepage flow for a long duration under such condition (though significant seaward hydraulic gradient could be observed during the same time period for 5 s and 10 s cases). Meanwhile, Fig. 4b shows the horizontal gradient in Region II varies concisely with a single crest under all three wave periods, presenting a much simpler temporal varying feature (increase rapidly towards land, then decrease slowly towards sea) than those observed in Region I (Fig. 4a). In region II, permanent landward seepage occurs under 5 s period condition, while the seepage direction changes alternately in 10 s and 20 s cases. Regarding the maximum horizontal gradient, it is largest for 10 s case, which is consistent with the situation of uprush limit (highest for 10 s case).

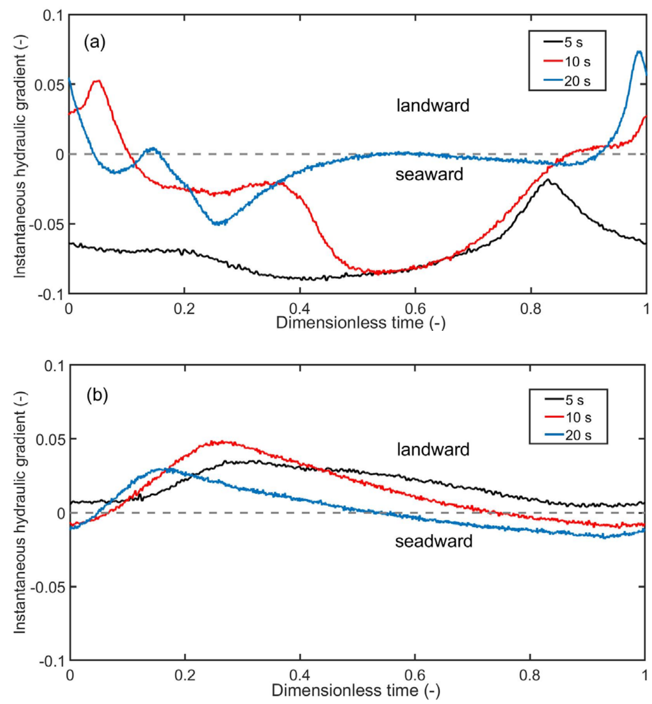

Fig. 4. Instantaneous horizontal hydraulic gradient at (a) x=40 cm (Region I) and (b) x=160 cm (Region II).

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