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Wave effects on submarine groundwater seepage measurement

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ABSTRACT

Variation of sea-surface and water pressure above the sea bed induces temporal variation of submarine groundwater discharge over time scales ranging from seconds to years. Hydrodynamic theory and measurements suggest that wave-induced exchange between a permeable sediment bed and overlying water column is significant but conventional seepage-meter studies have focussed mainly on tidal dynamics and ignored waves. At Cockburn Sound in Western Australia we measured wave-induced flow reversals through a seepage meter of amplitude 60 cm d^{-1}; however, it was unclear whether the measured flows were real seepage or, partly or wholly, an artifact of wave action on the seepage meter. A numerical model of seepage patterns beneath a vented benthic chamber demonstrated an observer effect introduced by the chamber and not previously identified. Placing a chamber on the sediment bed disturbed the pressure field and changed both the pattern and magnitude of the wave-induced flow. A separate analysis of benthic-chamber movements under the action of shallow surface waves established that micron-scale movements of the chamber at the wave frequency were sufficient to produce apparent seepage amplitudes of $O(1–100)$ cm d^{-1}. We concluded that wave action is a key control on bed seepage and should not be neglected without justification in direct-measurement studies of marine bed discharge. A systematic error during each wave cycle can accumulate to a significant measurement error if the wave cycle error is large or if wave-induced flow is the dominant component of the seepage. In the latter case, the error could potentially be misinterpreted as a steady seepage component.

1. Introduction

Sea-surface fluctuation induces water exchange between the sea and permeable bed sediments. Temporal variation of submarine groundwater discharge (SGD) in response to tides and longer-period sea-surface dynamics have been previously reported [21,9,40,20] but variation of SGD at subtidal frequencies remains largely un-investigated [27] and un-measured. This may be an oversight in many studies because accepted hydrodynamic theory suggests that the wave-induced component of SGD can be the same order-of-magnitude as both the tide-induced component and the freshwater—terrestrial component—albeit at a much shorter time scale.

Awareness about the biochemical and ecological significance of SGD has matured during the past 30 or so years. Groundwater has different quality to seawater and clear links between groundwater discharge and ecological zonation in marine environments have been found [15,32]. If groundwater fluxes across marine beds were uniform and steady then these relationships might be easy to study; however, groundwater seepage is notoriously difficult to quantify because it is spatially and temporally variable across a broad range of space and time scales. As pointed out by Burnett et al. [2] "reliable methods to measure these fluxes need to be refined and the relative importance of the processes driving the flow needs clarification and quantification".

In this study, seepage-meter measurements of SGD at Cockburn Sound in Western Australia exhibited flow reversals at the wave period but we were uncertain whether the fluctuations were real seepage induced by waves or an artifact of wave action on the seepage meter. Wave-induced flows are short lived, fluctuate rapidly compared to tides and watertable dynamics in the inshore aquifer, and penetrate only small distances into the sediment bed. Nevertheless, seepage meters are placed directly at the water–sediment interface and are theoretically sensitive to all fluid exchange between the sediment bed and the water column.

Wave-induced pore-water flow contributes a zero net groundwater flux to the sea because the sea is both the source and sink for the flow. The wave-induced component of seepage is normally overlooked in seepage-meter studies on the assumption that the device can accurately measure and sum to zero such fluctuations without significant error. Waves also may act mechanically on a benthic chamber to produce apparent seepage flows caused by subtle movements of the chamber relative to the sediment bed, or flexing of the chamber itself. The possibility that such fluxes oc-

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cur during seepage-meter studies has been noted by practitioners but not investigated theoretically or practically.

This paper explores the potential for wave-induced flow and measurement error during seepage-meter studies, including both real and apparent flows. The theory of wave-induced bed seepage is reviewed to confirm that real seepage of the magnitude observed in Cockburn Sound is theoretically feasible and consistent with the wave climate and sediment properties. The possibility that the measured fluctuations were an artifact of wave action on the seepage meter is then considered. Specifically, a model of wave-induced pressure fluctuation in the sediment bed beneath a vented benthic chamber is presented, and the potential significance of movement or flexing of the benthic chamber in response to the mechanical action of waves is analysed.

1.1. Description of wave-induced bed seepage

Pore-fluid motions caused by surface waves propagating over permeable beds were first studied by marine researchers investigating the interaction between bed percolation and wave-energy damping [23,25,26,19,12]. They found that sea water flows into the sediment bed beneath the propagating wave crests and pore-water efflux occurs beneath the wave troughs. For the case of free plane sine waves propagating over a flat, horizontal sediment bed (Fig. 1), the pressure-head field above the water–sediment interface, $h(x,z,t)$ [L], is usually given as [16]

$$h = (D - z) + \frac{\eta}{\cosh(k(D - z))}, \quad (1)$$

where D [L] is mean sea-surface elevation above the sediment bed, $\eta(x,t) = a\sin(kx - \omega t)$ [L] is the sinusoidal fluctuation of the sea-surface elevation, a [L] is the wave amplitude, $k = 2\pi/\lambda$ [L^{-1}] is the wave number, λ [L] is the wavelength, $\omega = 2\pi/P$ [T^{-1}] is the angular frequency, P [T] is the wave period, x is the horizontal coordinate in the direction of wave propagation, z is the vertical coordinate measured positive-upward from the water–sediment interface and t is time.

For an incompressible, homogeneous, isotropic and infinitely-thick sediment bed, and assuming Darcy flow, the pressure-head field below the water–sediment interface $\phi(x,z,t)$ [L], and the resultant amplitude of wave-induced flow across the interface q_a [$L\,T^{-1}$], are given by [23,25,26,11,12]

$$\phi = D + \exp kz \frac{\eta}{\cosh kD} \quad (2)$$

and

$$q_a = K\frac{ak}{\cosh kD}, \quad (3)$$

where K [$L\,T^{-1}$] is the sediment hydraulic conductivity. Eq. (3) provides a succinct estimate of the wave-induced seepage amplitude but it ignores important properties of the sediment bed that can affect seepage—such as compressibility, inhomogeneity and anisotropy [19]—and may have limited utility for predicting bed seepage under field conditions. The other difficulty in applying Eq. (3) to seepage-meter measurements stems from the fact that the benthic chambers used in those studies disrupt the pressure field on which the formulation is based. These issues are explored further in the paper.

1.2. A note on non-flat bed forms

This paper is concerned specifically with cyclic bed seepage that occurs in response to unimpeded wave motion over a flat bed form. It also considers the potential influx and efflux of fluid from the benthic chamber in response to movement of the chamber caused by the mechanical action of waves. It does not contribute to the investigation of bed seepage induced by steady surface currents moving over non-flat bed forms (e.g., dunes and ripples) [43,41,7,13,31,22] or impermeable obstructions on the sediment bed (e.g., partially buried rocks and benthic chambers) [14,29,4].

2. Results from previous seepage-meter studies

Seepage-meters studies of SGD have typically used measurement-integration periods that preclude the detection and analysis of wave-induced flows (Table 1). This does not mean that the measurements necessarily contain wave-induced errors, though it remains unclear whether wave action was significant in those studies and influenced the results.

Only one of the 20 seepage-meter studies listed in Table 1 reported seepage measurements at a temporal resolution that could demonstrate wave effects. Although those seepage measurements were taken in a lake [27] the results contained variation in the range ±300 centimetres per day ($cm\,d^{-1}$) in apparent response to wind-generated surface waves. The authors suspected that some of the flow variation was in response to flexing of the flat top of the benthic chamber. Riedl et al. [26], who did not use a seepage meter, also reported pore-water fluctuation at wave frequency of amplitude $O(164–389)$ ($cm\,d^{-1}$) based on the analysis of a "constant temperature hot-thermistor anemometer" placed within the upper 30 cm of a sandy sea bed.

It is clear from Table 1 that seepage rates of less than 1 $cm\,d^{-1}$ and typically within the range 1—100 $cm\,d^{-1}$) are reported in the hydrological literature. The implication is that seepage meters can resolve specific discharge across the sediment bed $O(0.1–10)$ micrometres per second ($\mu m\,s^{-1}$). Thus, 1 mm of seepage would take from 2 min to well over 2 h to emerge from the sediment. During that time it is further implied that the instrument can sum any bi-directional flow constituents without introducing an

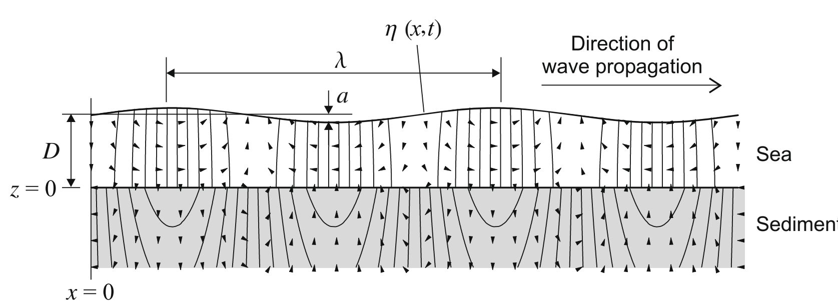

Fig. 1. Instantaneous isopotentials (lines) and velocity field (arrow heads) generated by free plane sine waves of the form $\eta = a\sin(kx - \omega t)$ propagating over a flat bed. In this example $D = 1$ m, $a = 0.1$ m, $\lambda = 45$ m, $P = 15$ s, $K = 5$ m d^{-1} and $t = 0$ s.