15th Australasian Fluid Mechanics Conference
The University of Sydney, Sydney, Australia
13-17 December 2004

Measurement and Modelling of Controlled Beach Groundwater Levels Under Wave Action

L.S. Ang, C.H-Y. Sum, T.E. Baldock, L. Li, and P. Nielsen,
Division of Civil Engineering, University of Queensland,
St Lucia, Qld 4072, Australia

Abstract

New laboratory scale experimental data are presented on the forcing of beach groundwater levels by wave run-up. The experimental setup simulates a coastal barrier dividing the ocean from a relatively constant back beach water level, conditions approximating a closed off lagoon system or beach aquifer. The data are critically compared to an advanced numerical model for simulating wave and beach groundwater interaction in the coastal zone, and provide the first experimental verification of such a model. Overall model-data comparisons are good, but some systematic discrepancies are apparent, and reasons for these are discussed.

Introduction

Groundwater levels in beaches and across coastal barriers and atolls play an important role in the mixing of fresh and saline water and the overall flux of nutrients and pollutants across the land-ocean boundary. Depending on the gradient of the water table, water, nutrients or pollutants may flow landward [7] or seaward [4]. The watertable slope is dependent on boundary conditions on the beach face and the landward water table level (see figure 1). The latter may be fresh water from rainfall on to the barrier, or from a creek or estuarine system behind the coastal barrier. The beach face boundary condition is controlled by tidal oscillations and wave induced setup and run-up on the beach face.

The beach groundwater level also controls the degree of infiltration or exfiltration into the beach, which in turn may influence sediment mobility on the beach face and overall beach morphology (e.g. [3,10]). However, attempts to modify beach morphology by controlling groundwater levels or through beach drainage have had mixed success (e.g. [8]). In part this may be due to the complex interaction between wave run-up and groundwater and uncertainties over the influence of infiltration/exfiltration on sediment transport. While analytical and numerical models for beach groundwater have been verified against data at tidal frequencies [6,1], no verification has been carried out for forcing at wave frequencies.

This paper considers this issue and presents new experimental laboratory data which are critically compared to results from a recent numerical model [5]. The results suggest that the model provides a good overall description of the data, particularly for raised groundwater levels. However, the model tends to under estimate the groundwater levels for longer period waves, while overestimating them for shorter period waves. Possible reasons for this are discussed with regard to the inner surf zone and swash zone hydrodynamics.

Background

Figure 1 shows a definition sketch of the coastal zone, where the backshore region consists of a coastal sand barrier/dune system dividing a creek, lagoon or estuary from the ocean. The water level in the creek, lagoon or estuary may oscillate at tidal frequencies if the system is open to the ocean, or be relatively constant if closed, changing only with rainfall or input from the catchment. In that instance, the backshore water level is fixed at some elevation that may be higher, lower or similar to the mean ocean level, which will vary according to tidal stage. Thus at high tide the groundwater level at the beach boundary may be raised above that inland, whereas at low tide it may be lower. Wave run-up subsequently further influences the groundwater levels in the beach.

The present paper simulates this scenario in carefully controlled laboratory experiments and provides measurements of the piezometric head levels in the beach. These are compared to predictions from the BeachWin model of Li et al. [5]. The model couples the non-linear shallow water wave equations with the Laplace equation for saturated flow in the beach, including capillary effects. Previous applications of the model show realistic simulations of the groundwater response to waves, but it has yet to be tested against experimental data. Such testing is reported below.

Experimental Setup

The experiments were carried out in a section of the Coastal Wave Basin at the University of Queensland. This section is approximately 30m long by 1.4m wide and was used with a working water depth of 0.5m. A model scale mobile sediment beach (d_{50}=0.84mm) was setup in the basin (figure 2), behind which the water table was controlled by means of an overflow system. The water level in the basin was kept constant using a small inflow near the wavemaker and a weir. A set of 20 damped manometer tappings on the bed of the flume provided time-averaged mean piezometric head levels from offshore of the breakpoint to the back of the beach.

For each run the initial beach shape was plane (gradient 1:7.6) with the beach was regraded between runs. Prior to running waves, the watertable behind the beach was set at a chosen level (nominally 0 to ± 0.075m) relative to the offshore level and the piezometric head levels recorded. A series of regular waves were then generated by the wavemaker, with the beach profile and piezometric head levels recorded at intervals of 10-20 minutes for a one hour period. Wave periods ranged from 1-2.5s, with wave heights between 0.05m and 0.15m. A total of 10 different wave conditions were run, each with at least 3 different back beach controlled water levels. The relative back beach water levels and wave heights were set so as to simulate the typical tidal range and wave heights on a micro-meso tidal beach. Further details may be found in Sum [9].

Modelling

The BeachWin model was setup identically to the experimental arrangement and using the measured hydraulic conductivity of the beach sediment (0.001m/s). The model was run in fixed beach mode, i.e. without profile evolution over time, to avoid errors in the sediment transport predictions feeding through into predicted piezometric head levels.

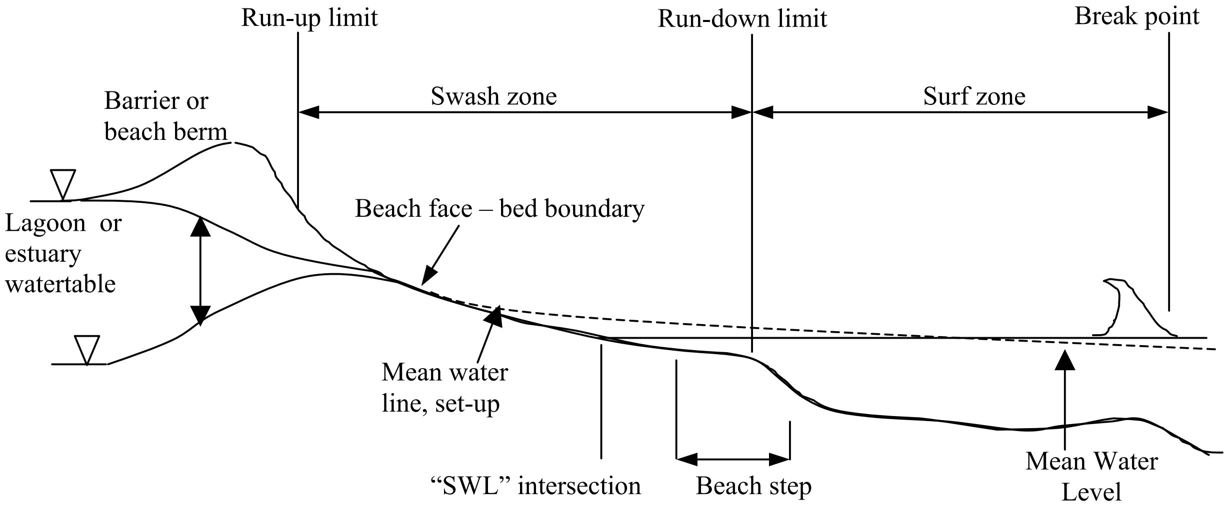

Figure 1. Definition sketch of nearshore zone, coastal barrier and beach groundwater levels.

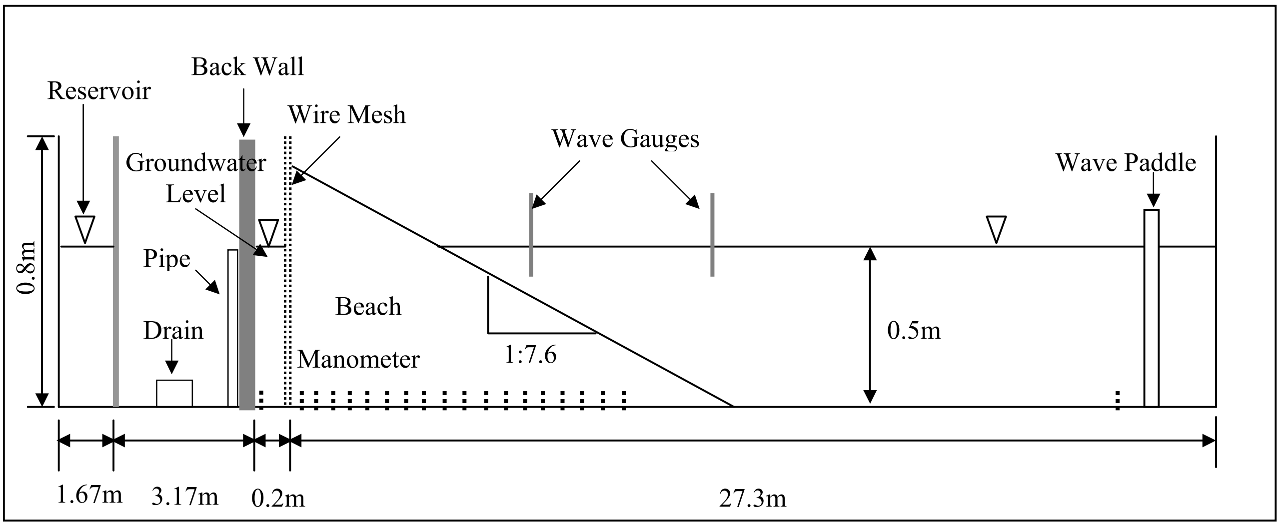

Figure 2. Wave flume, beach layout and instrumentation.

Model-data comparisons were therefore carried out only for measurements made at the first 10min sampling interval. At this time the groundwater level had reached equilibrium with the waves and beach morphology, but the changes in morphology from the initial plane state were small. Subsequent tests suggested that later changes in morphology lead to only minor changes in overall piezometric head levels. Differences between model predictions for small changes in morphology are also minor. Hence, taking the beach boundary as the initial plane state has a very minor effect on the model predictions and model-data comparisons.

Results

Figure 3a shows an example of the initial beach profile, the beach profile after 10min, together with the still water line (SWL) and the measured and modelled piezometric heads (denoted BW). The wave conditions and back beach head level are indicated in the caption. While significant profile evolution occurs, this has little effect on the measured or modelled head levels, which are primarily governed by the back beach head level and the wave run-up limit [7]. In this instance the back beach head level was controlled to be similar to the offshore water level, simulating a mid-tide condition, micro-tidal beach or spit between the arm of an estuary and the ocean.

Figure 3b shows the measured and modelled piezometric heads for the same wave conditions but with the back beach water level held lower than the offshore water level, simulating high tide conditions. Figure 3c shows similar data, but simulating low tide conditions (offshore water level below the back beach level). In both instances the model appears to overestimate the head levels in the surf zone (x=1.5m corresponds to the intersection of the initial beach profile and the SWL), but underestimates them in the swash zone and within the beach, particularly for the high tide scenario.

With a shorter wave period (f=0.6Hz) but the same wave height (H=0.15m), the model-data comparisons are good for the mid-tide and high tide conditions (figures 4a and 4b), but the model shows a systematic over-estimation of the head levels for the low tide case (figure 4c). The reason for this appears to be a significant overestimation of the wave setup in the inner surf zone and this may be related to the energy dissipation routine within the model.

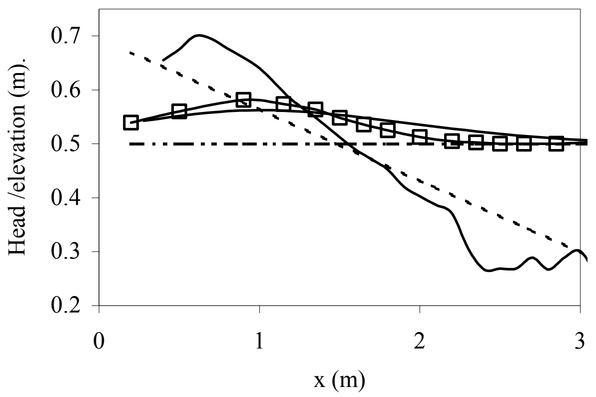

Figure 3a. Beach profile evolution and piezometric head.
f=0.4Hz, H=0.15m, TWL=0.54m.
—— BW; —□— measured; — ·· — SWL
– – – profile, t=0; —— profile, t=10mins.

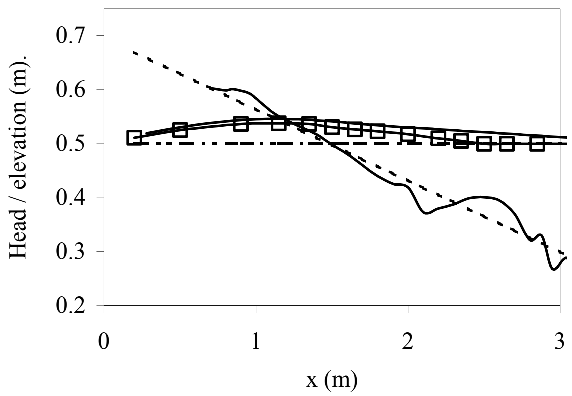

Figure 4a. Beach profile evolution and piezometric head.
f=0.6Hz, H=0.15m, TWL=0.511m.
—— BW; —□— measured; — ·· — SWL
– – – profile, t=0; —— profile, t=10mins.

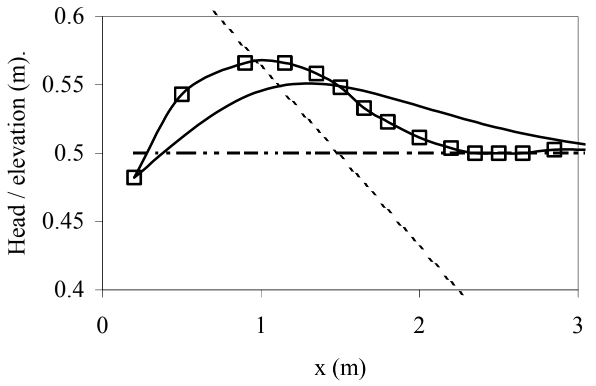

Figure 3b. Modelled and measured piezometric head,
f=0.4Hz, H=0.15m, TWL=0.48m.
—— BW; —□— measured; — ·· — SWL; – – – profile, t=0

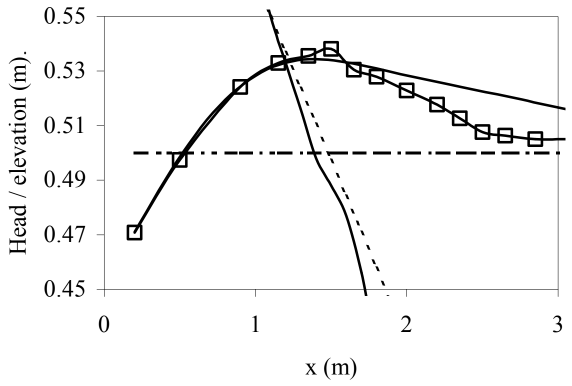

Figure 4b. Modelled and measured piezometric head,
f=0.6Hz, H=0.15m, TWL=0.471m.
—— BW; —□— measured; — ·· — SWL; – – – profile, t=0

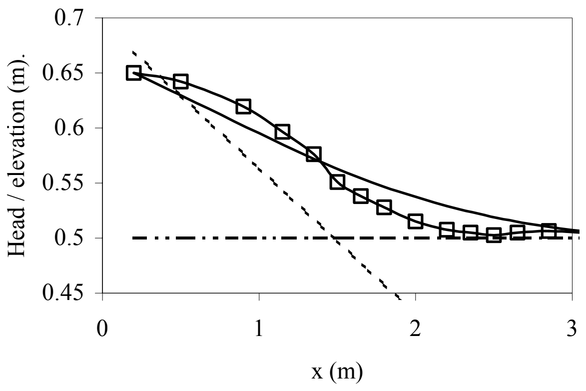

Figure 3c. Modelled and measured piezometric head,
f=0.4Hz, H=0.15m, TWL=0.65m.
—— BW; —□— measured; — ·· — SWL; – – – profile, t=0

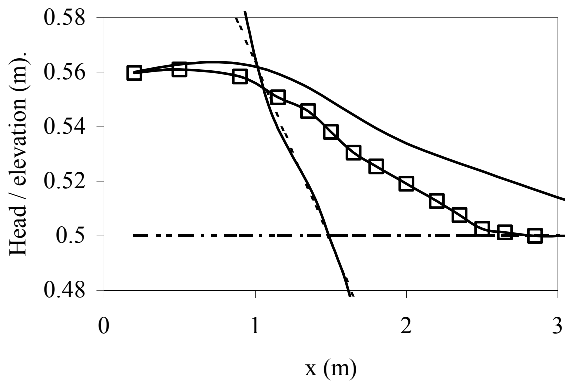

Figure 4c. Modelled and measured piezometric head,
f=0.6Hz, H=0.15m, TWL=0.56m.
—— BW; —□— measured; — ·· — SWL; – – – profile, t=0

The two main boundary conditions influencing the beach groundwater head levels are the back beach water level and the surf zone setup due to waves. These interact through the flow within the beach and model-data comparisons of this are illustrated in figure 5. For longer wave periods the back beach water level appears to have little effect on the head offshore of the initial shoreline (figure 5a and 5b), indicated by near constant setup in the surf zone, irrespective of the back beach water level. The model results are in good agreement with the data in this respect. However, for the low-tide condition, the influence of the back beach water level is not so well predicted, as demonstrated by the different shape of the modelled and measured head profile (see also figure 3c).

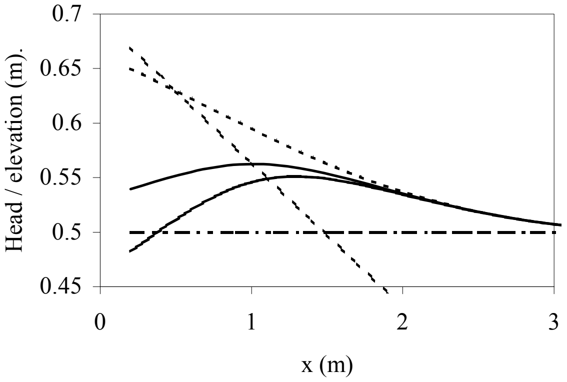

Figure 5a. Modelled piezometric head,
f=0.4Hz, H=0.15m, varying TWL, as figure 3 above.
— ·· — SWL; – – – profile, t=0

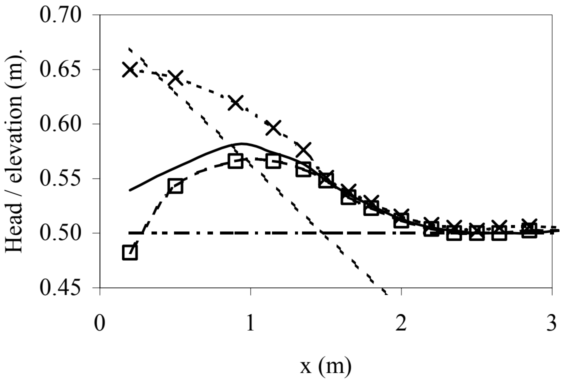

Figure 5b. Measured piezometric head,
f=0.4Hz, H=0.15m, varying TWL.
— ·· — SWL; – – – profile, t=0

For a shorter wave period and smaller wave height (f=1Hz, H=0.1m) the measured data show that the back beach ground water level can influence the setup in the inner surf and swash zones, with smaller setup observed for a lower overall beach groundwater (figure 6b). However, the model does not predict this, and indeed shows an opposite trend which does not seem entirely realistic. The observations are consistent with the influence of swash-swash interactions on nearshore setup, which becomes proportionally larger for shorter period waves [2]. While this interaction process can be simulated by the model, it is clear that some discrepancies remain.

Conclusions

Numerical model results have been compared to new experimental laboratory data on beach groundwater levels forced by wave-runup. Overall model results are encouraging and suggest the model may be a useful tool to study wave-induced beach groundwater interactions. Model-data discrepancies appear to be a result of inaccurate prediction of the nearshore hydrodynamics, as opposed to poor representation of the internal flow in the beach.

Acknowledgements

The authors gratefully acknowledge support and funding from the Australian Research Council, the CRC for Sustainable Tourism and the University of Queensland.

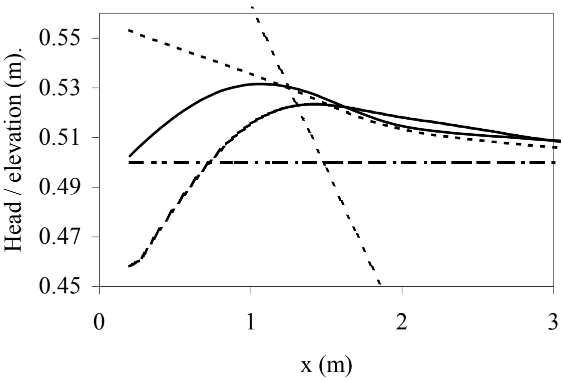

Figure 6a. Modelled piezometric head,
f=1Hz, H=0.1m, varying TWL.
— ·· — SWL; – – – profile, t=0

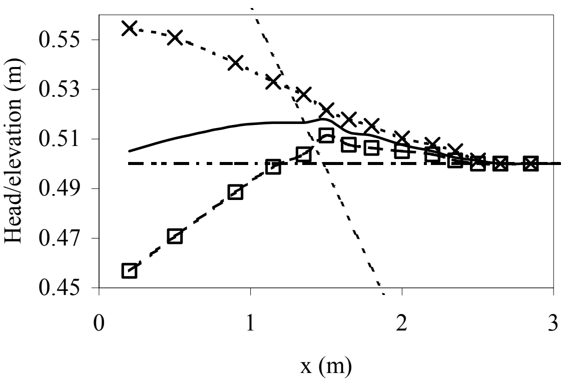

Figure 6b. Measured piezometric head,
f=1Hz, H=0.1m, varying TWL. — ·· — SWL; – – – profile, t=0

References

[1] Baird, A.J., Horn, D.P. and Mason, T.E. Validation of a Boussinesq model of beach ground water behaviour. *Marine Geology*, 148, 1998, 55-69.

[2] Baldock, T. E. and Holmes, P., Simulation and prediction of swash oscillations on a steep beach. *Coastal Engineering*, **36**, 1999, 219-242.

[3] Grant, U.S. Influence of the water table on beach aggradation and degradation. *J. Mar Res*., **7**, 1948, 655-660.

[4] Li, L., Barry, D. A., Stagnitti, F. and Parlange, J.-Y. (1999): Submarine groundwater discharge and associated chemical input to a coastal sea, *Water Res. Research*, **35**, 3253-3259.

[5] Li, L., Barry, D. A., Pattiaratchi, C.B., and Masselink, G., BeachWin: modelling groundwater effects on swash sediment transport and beach profile changes. *Environmental Modelling & Software*, 17, 2002, 313-320.

[6] Nielsen, P., Tidal dynamics of the watertable in beaches. *Water Resources Research*, **26**, 9, 1990, 2127-2135.

[7] Nielsen, P., Groundwater dynamics and salinity in Coastal Barriers, *J. Coastal Res*., **15** (3), 1999, 732-740.

[8] Oh, T.M. and Dean, R.G. Effects of controlled water table on beach profile dynamics. *Proc. Int. Conf. Coastal Engineering*, 3, 1994, 2449-2460.

[9] Sum, CH-Y., Influence of beach groundwater levels on beach morphology. University of Queensland, 2004. 92pp.

[10] Turner, I.L. and Masselink, G., Swash infiltration-exfiltration and sediment transport, *J. Geophys. Res*., **103**, 1998, 30813-30824.