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Understanding porewater pressure response in a dyke foundation soil under a hypertidal environment

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ABSTRACT: Climate change poses a significant threat to low-elevation marine coastal zones, where rising sea levels and intensifying storms are expected to increase coastal flooding. In Nova Scotia, Canada, earthen dykes were built by French settlers in the 1600s and 1700s to reclaim low-elevation areas for agriculture development. These dykes span 241 km along the Bay of Fundy, now safeguarding both agricultural and urban lands. Rising sea levels put these structures at risk of overtopping and eroding, prompting government efforts to increase their height and armoring.

The Bay of Fundy experiences a tidal range up to 17 m which results in coastal waters being present near the dykes for only small periods of time (several hours) each day or, in some cases, each fortnight. This hypertidal environment creates unique questions regarding the porewater response of dykes and dyke foundation soils during semi-diurnal and fortnightly (spring-neap) cycles of the tides as well as the contribution of seepage to the porewater conditions within and under the dykes. To better understand porewater pressure response to these intermittent tidal loadings, foreshore soils near an existing dyke were instrumented with vibrating wire piezometers to observe porewater pressure responses throughout a tidal cycle. In-situ and lab testing were also performed to establish basic soil characteristics. Modelling was then performed to assess the relative contribution of seepage compared to total stress loading of the foundation soils as it relates to the porewater pressure response of the foundation soils. The modelling results suggest that porewater pressure response due to the tidal signal is likely resulting mostly from the total stress loading of the tide applied to the surface of the foundation soils. The results of this study are intended to inform future studies related to the porewater changes in dyke structures induced from construction of dyke heightening.

KEYWORDS: dyke, tidal, porewater pressure, monitoring, modelling.

1 INTRODUCTION

The reclamation of marginal coastal land via earthen dykes is commonplace around the world (e.g. Almeida et al. 2014). These earthen dykes are often placed on marine estuary/salt marsh environments that contain poorly draining, soft, unconsolidated soils. Many of these dykes have been built hundreds of years ago (Bleakney, 2004) with slow hand-based construction methods in which undrained stability issues were minimized. More recently, there are elevated concerns related to the effects of climate change on rising sea levels which require many of these dykes to be raised in height (Sherren et al., 2021). Understanding the response of excess porewater pressure development in these dyke soils allows a better understanding of porewater pressure dissipation during dyke heightening as well as porewater pressure development within the dykes during high tide conditions.

On Canada's eastern coast, in the province of Nova Scotia, earthen dykes were built by French settlers in the 1600 and 1700s to protect reclaimed land in the low-elevation areas near marine environments. Here there are more than 240 km of earthen dykes along the Bay of Fundy, safeguarding urban and agricultural lands. The Bay of Fundy is a unique tidal environment given the pronounced tidal range is as high as 17 m arising from the resonance of the Bay's natural period with the M2 tidal constituent (Garrett, 1972). Due to climate change, these earthen structures are at risk of overtopping at present heights, prompting government efforts to increase their height (CBC, 2025). Most of these dykes are constructed on soft, poorly drained marine-based organic silts that require slow construction during dyke heightening to allow for excess porewater pressure dissipation and subsequent gain of undrained shear strength. There is also a surprising lack of information on the nature of the porewater pressure response within the dykes themselves during high tide events which complicates effective stress stability analyses for future dyke heightening projects.

This paper examines the porewater pressure response in the foreshore foundation soils near a dyke structure along the Bay of Fundy, Canada. The hypertidal environment (17 m range) creates a unique opportunity to examine these questions of porewater pressure response of the dyke foundation soils during rapid loading conditions (i.e., the semi-diurnal cycle of the tides) due to the relatively undrained loading of the foundation soils from the tides. In the paper, we will present a summary of the site conditions, details of the piezometer installation, porewater pressure response during a selected tidal cycle and the results of finite element modelling to examine the mechanisms responsible for the observed porewater pressure response.

2 FIELD MEASUREMENTS

2.1 *Site description*

The field site is located near an existing earthen dyke in Avonport, Nova Scotia, Canada. This dyke was constructed over 300 years ago by Acadian settlers in the area to reclaim salt marshland for agricultural purposes. The soil conditions in this area of the dyke were previously investigated by WSP (2022) in conjunction with a proposed future dyke heightening and armoring project. Details on the construction method for these dykes have previously been reported by Bleakney (2004) but they were generally constructed from adjacent soils and sods. Near the study site, there is an aboiteau structure that allows runoff from behind the dyke to exit through the dyke during low tide conditions but prevents seawater from entering through the dyke during high tide conditions. An aerial photo of the study site is presented in Figure 1.

Figure 1. Drone photo of study site. Dyke crest is approximately 3 to 4 m wide for scale.

In the vicinity of the piezometer installation for this project, various geotechnical lab testing was performed on samples obtained using the methods described by Rosvall (2024). During sampling, it was observed that the macrostructure of the soils contained organic matter such as roots and seagrass. Figure 2 shows a photo typical of the organic matter observed in these samples. The details of testing performed on the soil are presented in Table 1.

Figure 2. Photo of organic silt material sampled as part of the investigation of the study area. Sample is approximately 2 cm thick for scale.

Table 1. Summary of lab and field testing performed on soil.

Parameter	Symbol	Range	Unit
Water content	w	45-155 (n=17)	%
Plastic limit	PL	33-37 (n=6)	%
Liquid limit (air dried)	LL	66-72 (n=3)	%
Compression index	C_c	0.29-37 (n=2)	-
Coefficient of consolidation	c_v	10^{-7} (n=2)	m^2/s
Hydraulic conductivity (back-calculated from consolidation tests)	k_c	10^{-9} (n=2)	m/s
Hydraulic conductivity (falling head tests in field)	k_f	10^{-8} (n=2)	m/s

2.2 *Tidal monitoring and piezometer information*

Tide elevations (geodetic) were recorded using a tidal stilling well described by Rosvall (2024). The tide elevations during one sample month of the piezometer monitoring are shown in Figure 3. During this month, the spring tide and neap tides as well as the variation in high tides throughout the month, are evident. It should be noted that the "bottoming out" of the tide levels in Figure 3 does not represent the actual low tide level, but rather when tidal waters dropped below the location of the logger.

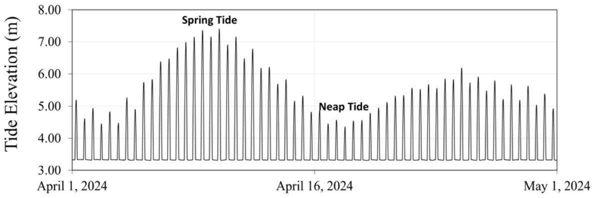

Figure 3. Tide elevations (geodetic) for one month period near piezometer PM2.

Four piezometers were installed as part of an overall research project in the foreshore (intertidal zone) shown in Figure 1 at various depths. However, only results from one piezometer (PM2) for one tidal cycle at the spring tide shown in Figure 3 are examined in this paper. The vibrating wire piezometer PM2 was installed at a depth of 1.5 m in the foreshore soils at the site, as shown on Figure 1. The piezometer was obtained from RST Instruments Ltd. (model VW2100-0.07) and logged with a 5/10 channel data logger (model DT2055B). The data acquisition software was DT Logger Host version 1.20.0 (May 23, 2023). The VW2100 piezometers have a pressure range of 0.07 MPa. A fully grouted approach (Mikkelsen, 2003) was used to install the piezometer. This method included hand auguring a borehole, mounting the piezometer to an acetal copolymer resin (i.e. plastic) acrylic support rod, placing the assembly in the borehole, and completely filling the borehole with a cement-bentonite grout. The hydraulic conductivity of the grout was designed to be near or slightly less than that of the surrounding soil to avoid vertical transmission of a signal along the borehole (McKenna, 1994). A mix ratio of water, cement, and bentonite of 6.5:1:1.2 was used for this study. Details are provided in Rosvall (2024).

3 MODELLING OF PM2 RESPONSE DURING SPRING TIDE

Finite element modelling was performed to examine predicted porewater pressure responses compared to measured porewater pressure responses when the range of measured hydraulic conductivity values obtained from field and lab testing (10^{-8} to 10^{-9} m/s) was used. The goal was to examine the role of seepage in the porewater pressure response (if any) compared to porewater pressure response developed from changes in total stresses. Modelling of the piezometer porewater pressure response to the tidal signal was performed using the two-dimensional finite element programs SEEP/W and SIGMA/W in GeoStudio. SIGMA/W allowed for coupled water flow and stress-deformation behavior within the soil. A two-dimensional model geometry was defined, as shown in Figure 4. Soil properties were defined as saturated and assigned drained behavior. The modeling was conducted using an isotropic elastic model for the soil. This admittedly incorporates some simplicity to the model. Given the small change in effective stress exerted by the tidal signal, the assumption of elasticity was deemed reasonable. The soil is likely not isotropic; however, the purpose of this paper is to investigate processes rather than exactly reproduce observed behaviour. Thus, the isotropic assumption also was deemed reasonable. Given the relatively flat ground and low hydraulic conductivity in the vicinity of PM2, it was assumed for modelling purposes that the geometry could be simplified as shown in Figure 4 to examine mechanisms of porewater pressure response of the piezometer.

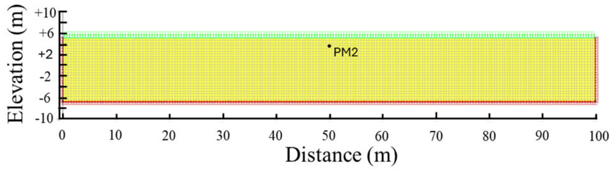

Figure 4. Model domain in Geostudio.

To establish the initial porewater pressures for the model, a steady-state SEEP/W analysis was used. In the steady-state SEEP/W analysis, a constant total head of 5.16 m was applied as the boundary condition on all domain boundaries based on piezometer readings at the location of PM2. The results of this analysis were then used as the "parent" analysis to define the initial porewater pressure distribution for subsequent coupled (combined flow and stress-deformation) analyses in SIGMA/W. Following this, a SIGMA/W in-situ analysis was performed using these initial porewater pressure conditions from SEEP/W to define the initial stress and deformation conditions for the coupled analysis. This was followed by transient coupled analyses conducted using SIGMA/W to simulate pore-water pressure changes throughout the soil column under tidal signal effects. Displacements were fully fixed in both X and Y directions at the bottom of the model domain and were restricted in the X direction along the vertical edges. Tidal fluctuations were applied at the top boundary as both hydraulic and stress/deformation boundary conditions, reflecting the effect of water flow through the soil and surface water weight variation over time. Figure 5 shows the water total head changes over time used for the upper boundary condition based on the tide levels measured for that particular spring tide condition. Finally, the coupled analysis was repeated for soils with different values of hydraulic conductivity to assess the sensitivity of the system response to this parameter. A summary of some of the key parameters assumed from the model is presented in Table 2.

Table 2. Summary of soil parameters used in modelling.

Parameter	Symbol	Value	Unit
Saturated unit weight	γ	19	kN/m^3
Effective elastic modulus	E	1	MN/m^2
Hydraulic conductivity	k_v	10^{-8}, 10^{-9}	m/s
Anisotropy ratio	k_h/k_v	1	-
Poisson's ratio	v	0.3	-

4 RESULTS AND DISCUSSION

Figure 5 shows the tide elevation at the location of PM2 for the spring high tide cycle on April 10, 2024 (dotted line). As previously discussed, this was also the top boundary condition used in the modelling process. Shown on this same figure is the field-measured PM 2 piezometer readings, also expressed in terms of total head. At the start of the tidal signal (time 0 hours), the total head in the piezometer is similar to that for the tide (i.e. no water above PM2). The small difference relates to a total head in the piezometer which is slightly higher than the ground surface at the beginning and the end of the tidal cycle, likely due to the poorly draining sediments and the previous tide cycle. As the tide begins to flood the ground surface above PM2, the piezometer reading rises in response to the change in the total head of the tidal signal. However, the total head in the piezometer signal becomes "separated" from the tide signal.

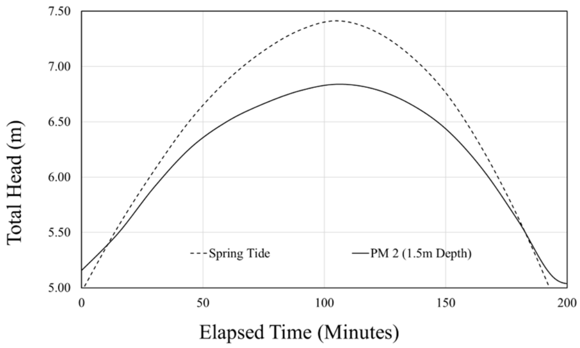

Figure 5. Comparison of surface water tidal signal to the piezometer PM2 response over a spring tide cycle on April 10, 2024.

To elucidate mechanisms responsible for this porewater pressure response in PM2, conventional groundwater flow modelling was performed using SEEP/W. This type of model will predict changes in total head in PM2 due to groundwater flow only, neglecting the role of water changing the total stress at the ground surface but allowing for a change in total head at the ground surface. Results are shown below in Figure 6 for two hydraulic conductivities (i.e. 10^{-8} to 10^{-9} m/s, Table 1) which represent the range of measured values in the field and lab for this study. With these hydraulic conductivity values, very little change in total head is predicted via the model (i.e. modelled values are predicting no response of the piezometer during the tidal signal). At these low hydraulic conductivities, very little seepage is simulated during the short tidal cycle. Using higher hydraulic conductivities (not shown in this paper), the model predicted a greater response of the piezometer during the tide cycle but with the peak of the piezometer reading delayed (phase shifted) from that measured. This is due to the time it takes for total head changes to occur due to water flow. Given the poor match of modelled data with the phase of the measured data using this seepage modelling approach with the measured k values of the soil, it can be concluded in these low hydraulic conductivity dyke foundation soils, total stress changes at the ground surface must be playing a significant role in the measured piezometer responses during the tidal cycle.

To further explore the role of the total stress applied to the ground surface by the tidal cycle, coupled analyses performed with SIGMA/W using the same range of hydraulic conductivities used for the SEEP/W modelling is shown in Figure 7. Methods for this modelling were described previously in the paper. As shown in Figure 7, the modelled results of SIGMA/W reasonably approximate the measured tide signal, but result in an overprediction of that measured from PM2. For the boundary conditions considered in this study, it appears there is very little drainage of excess porewater pressure predicted by SIGMA/W at the location of PM2 from the total stress application. Examining the measured response of PM2, there is in fact some "separation" of piezometer reading from the modelled value. The reasons for this difference could be due to a multitude of factors which are beyond the scope of this paper but deserve some speculation. It should be noted that this observation (i.e. separation of measured from modelled) was present at all four piezometers in the overall study, each installed at different depths.

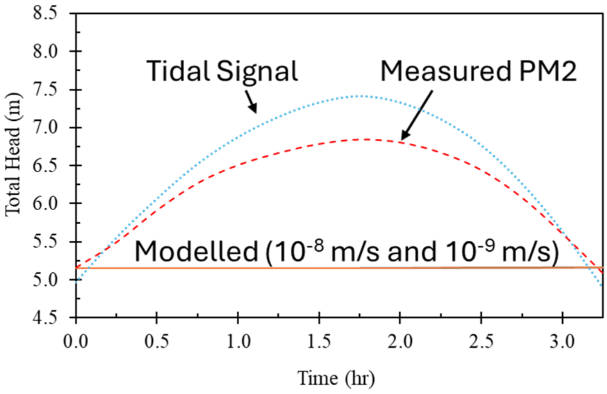

Figure 6. Predicted piezometer PM2 response over spring tide cycle on April 10, 2024 using SEEP/W.

One potential reason for this difference could be "leakage" of excess porewater pressure from either the grout/soil interface or the grout/acrylic rod interface. Another potential cause for differences could be due to fine sand and silt partings present in the sediments which allow some lateral drainage of excess porewater pressures generated in the sediment during the tide cycle. Sand/silt partings were observed during sampling and test pits performed on the study site. Thirdly, the assumption of porewater pressure response being equal to the total stress applied at the ground surface may not always be the case, as has been shown by Tavenas and Leroueil (1980) for embankment loadings of soft, compressible soils. This may be due to slight overconsolidation of the soils and/or soils that are unsaturated. For the foreshore soils presented in this study, it is possible that there are slight contributions from each of these factors. However, the exact cause warrants further investigation and will be the subject of future research.

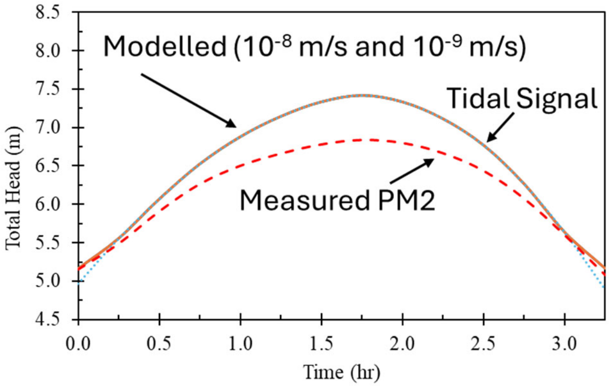

Figure 7. Predicted piezometer PM2 response over spring tide cycle on April 10, 2024 using SIGMA/W.

The impetus for this study was to better understand porewater pressure response in these soils from these hyper-tidal conditions which result in short "pulses" of total head and total stress applied to the soil surface. The overall goal of the research being performed is to better understand porewater response in earth dykes built on and built from these same soils when subjected to high tide levels. Currently there is a lack of information related to the water levels in the earthen dykes due to this short, transient loading (1-2 hours, twice a day). Water levels within the dykes play a large role in effective stress stability analysis, and the lack of understanding can cause for unnecessary conservative designs to be developed for future dyke heightening projects. Current research is underway for monitoring porewater pressure within an earthen dyke during tidal loading.

5 CONCLUSIONS

This investigation provided insights into the behavior of soft, low-permeability foreshore soils subjected to hypertidal loading in a coastal dyke system. Field measurements from a vibrating wire piezometer during a spring tide cycle showed that the total head response deviated from the tidal signal, a behavior not predicted by traditional groundwater seepage modelling with low hydraulic conductivities. Coupled hydro-mechanical modelling using SIGMA/W more closely approximated the response, underscoring the importance of including total stress effects in simulations of porewater pressure under rapid surface loading. However, differences between measured and coupled modelled results suggest that additional mechanisms such as local drainage through sand/silt partings, piezometer installation factors, or partial saturation effects may also influence response. Understanding these complex interactions is critical for improving predictive models and optimizing the design and construction methods for future dyke upgrades in similarly challenging geotechnical settings.

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