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Long Term In Situ Measurements of the Volumetric Water Content in a Soil Bentonite Slurry Trench Cutoff Wall

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ABSTRACT

This paper presents the results of a field study to assess post-construction changes in the volumetric water content (θ) of a soil-bentonite (SB) slurry trench cutoff wall. Time domain reflectometry (TDR) sensors were installed in a newly-constructed SB cutoff wall in the summer of 2008 and were used to monitor θ as a function of depth within the SB backfill for approximately one year. The methods used to install the probes are described and the measured θ distributions are presented and discussed. A general trend of decreasing θ with time was observed at all sensor locations. Decreases in θ within the portion of the wall below the water table are attributed to backfill consolidation, whereas the larger decreases in θ near the top of the wall (above the water table) are likely due to a combination of backfill consolidation and backfill drying. A field sampling program is recommended to confirm the moisture profiles obtained from the TDR sensors.

INTRODUCTION

Soil bentonite (SB) slurry trench cutoff walls are commonly employed as a means to control groundwater flow and contaminant migration. The methods by which these walls are constructed necessitate that the final wall material, i.e., the SB backfill, be placed at very high slumps (100-150 mm) with the moisture content approaching the liquid limit. Thus, the backfill is saturated (or nearly so) at the time of placement and is highly compressible (Filz et al 1991, Baxter et al 2005). Stress development and consolidation of the backfill material within these trenches is not fully understood (Ruffing et al 2010), but an understanding of the *in situ* stress state is important for accurate permeability estimation in the laboratory (LaGrega et al 2000, Filz et al 2003). The permeability of an element of SB backfill is strongly dependent on the effective confining stress on the element, even at the low stress ranges observed in these walls (Filz et al 1991, Evans 1994, Yeo et al. 2005, Ruffing and Evans 2010). The research effort on SB walls has been largely limited to laboratory investigations despite the need for an understanding of how the stress develops *in situ* (National Research Council 2007).

In the summer of 2008, researchers at Bucknell University capitalized on an opportunity to perform *in situ* testing and install long term monitoring equipment in an SB wall located in eastern Pennsylvania. The results of some of the *in situ* tests (i.e., cone penetration and dilatometer tests) have been described in previous publications (Ruffing 2009, Ruffing and Evans 2010, Ruffing et al 2011), with focus on the estimation of shear strength and lateral earth pressure in the backfill. This paper documents the results of additional *in situ* testing to assess changes in moisture content of the SB backfill with depth and over time. Time domain reflectometry (TDR) sensors were installed in the wall on the day of construction and were used to obtain volumetric water contents (θ) at various depths within the wall. The methods used to install the TDR sensors and analyze the sensor data are described and the resulting moisture profiles are presented and discussed.

MATERIALS AND METHODS

A soil-bentonite (SB) slurry trench cutoff wall was constructed under the technical guidance of Geo-Solutions Inc. to control ground water flow beneath a municipal wastewater facility in Birdsboro, PA. A flood control dike, built over the SB wall, was built to limit inflow of ground water such that below grade wastewater tanks do not become buoyant during flooding events of a nearby river. The barrier wall is approximately 1400 m^2 and 4.5 m deep at its deepest point. The backfill was a mixture of excavated soil, dry bentonite, and bentonite-water slurry and was placed as a thick viscous liquid (much like high slump concrete). From the field quality control data, the backfill unit weight varied from 17.3 to 21.0 kN/m3, the fines content from 41% to 55%, the slump from 51 to 146 mm and the placement water content from 24% to 51% (Ruffing and Evans 2010). After completion of the cutoff wall, the equilibrium upstream and downstream water table was found to be at depths of 1.5 m and 3.3 m below the top of the wall, respectively.

The sensors used in this study were Campbell Scientific (Logan, UT) Model CS615 TDR sensors. These sensors measure θ by monitoring the period of an electronic signal that travels along two parallel metal prongs. The period of the signal is obtained using a laboratory calibrated data logger and is correlated to θ. The probes were installed immediately after backfill placement using a PVC pipe to push the probes into position. In order to ensure that the prongs remained parallel during placement in the wall, the prongs were inserted in a PVC casing that was selected to fit snugly around the prongs. The casing and prong orientation in the trench are shown in Fig. 1 and the depths of the six sensors shown on Table 1.

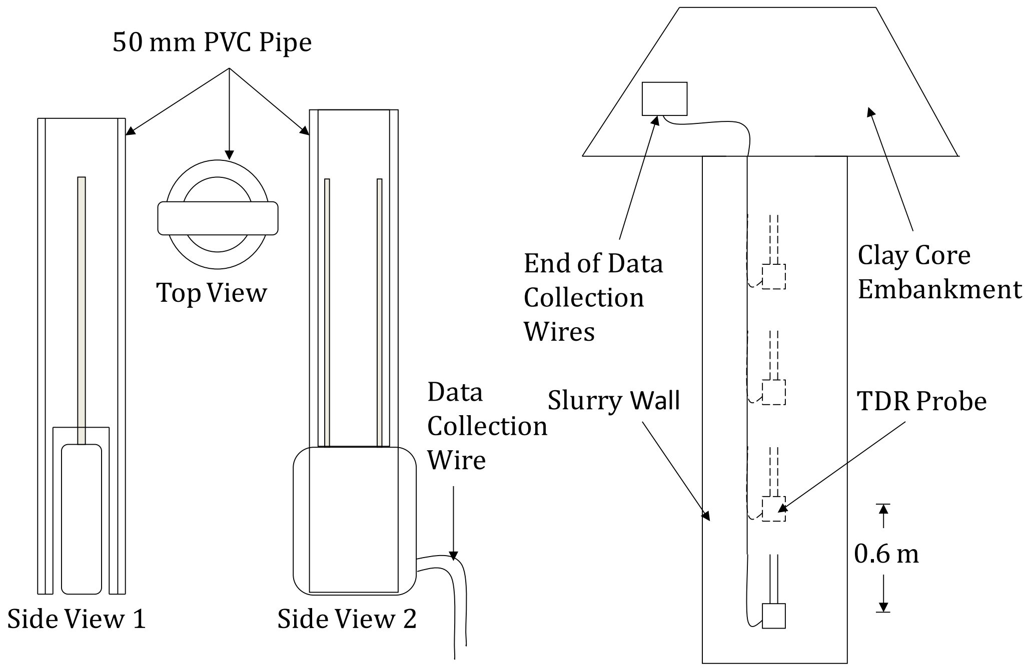

FIG. 1. TDR sensor installation and orientation schematics

Laboratory calibration of the TDR sensors was performed in a 0.019 m^3 (five gallon) bucket using grab samples of the backfill collected from the top of the slurry wall immediately after placement. The grab samples were dried in the laboratory to vary the gravimetric water content of the backfill and probe readings were taken in the dried backfill (Ruffing 2009). The resulting calibration curve is presented in Figure 2. The relationship between calculated VWC and the probe output VWC was linear over the range of values tested in the laboratory.

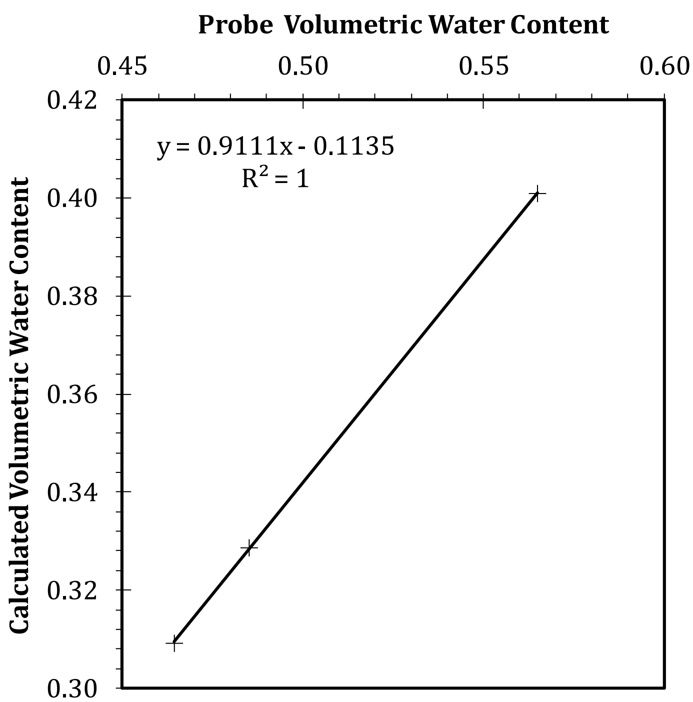

FIG. 2. Calibration curve for TDR sensors

Maintaining parallel prongs is very important for accurate estimation of θ (Campbell Scientific 2008). Despite efforts to maintain parallel prongs during insertion of the sensors, the authors believe that some of the prongs were distorted to some degree. This deviation from parallel necessitated a method of correcting the information collected from the sensors. The initial θ of the backfill, θ_o, measured by laboratory testing of bulk grab samples collected at the time of backfill placement, was 0.41 and was assumed to be uniform with depth in the wall. Based on this assumption, a correction factor (CF) was developed for each sensor based on the ratio of the laboratory θ_o to the value of θ_o given by the sensor, as follows:

$$CF = \frac{\theta_o\,(lab)}{\theta_o\,(sensor)} \tag{1}$$

The CF values for each sensor were then used to correct all subsequent (raw) readings of θ given directly by the sensors over the ~12-month monitoring period, as follows:

$$\theta_{corrected} = \theta_{raw} \cdot CF \tag{2}$$

RESULTS AND DISCUSSION

The probe correction factors given by Eq. 1 are shown in Table 1 along with the corrected values of θ as a function of depth below the top of the wall.

Table 1. Summary of corrected volumetric water content data.

		Corrected Volumetric Water Content, θ				
Depth (m)	**Correction Factor**	**7/29/08**	**9/22/08**	**11/19/08**	**3/4/09**	**6/11/09**
1.22	1.12	0.41	0.37	0.36	0.31	0.33
1.82	0.49	0.41	0.30	0.29	0.27	0.28
2.43	0.61	0.41	0.32	0.32	0.31	0.31
3.04	0.69	0.41	0.33	0.33	0.32	0.32
3.65	0.74	0.41	0.39	0.38	0.37	0.36
4.26	0.55	0.41	0.39	0.38	0.37	0.37

The corrected θ values also are plotted in Fig. 3 for each date that the sensor data were recorded. The sensors were read on the day of installation (July 24, 2008) and thereafter at 60, 118, 223, and 322 days after the day of installation. As shown in Fig. 3, the corrected data indicate a general trend of decreasing θ with time at all the sensor locations. The decreases in θ are likely due, at least in part, to self-weight consolidation of the soft backfill and additional consolidation due to the dike surcharge. In addition, the backfill above the downstream water table may have experienced some additional loss of moisture due to

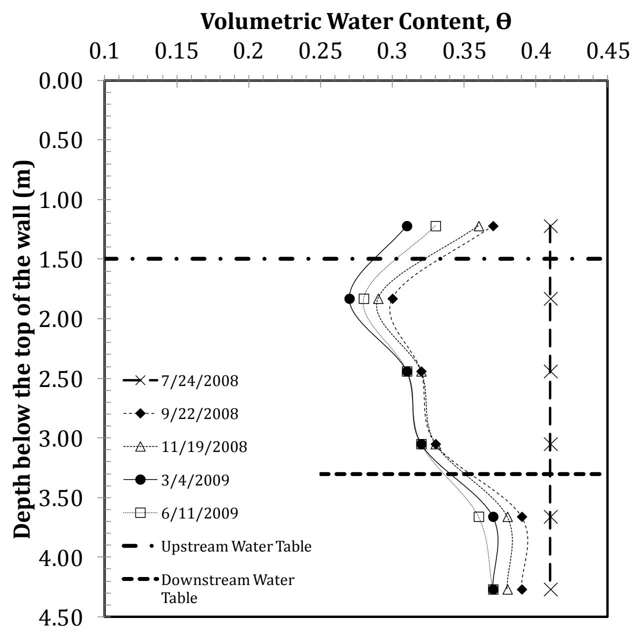

FIG. 3. Corrected θ vs. Depth

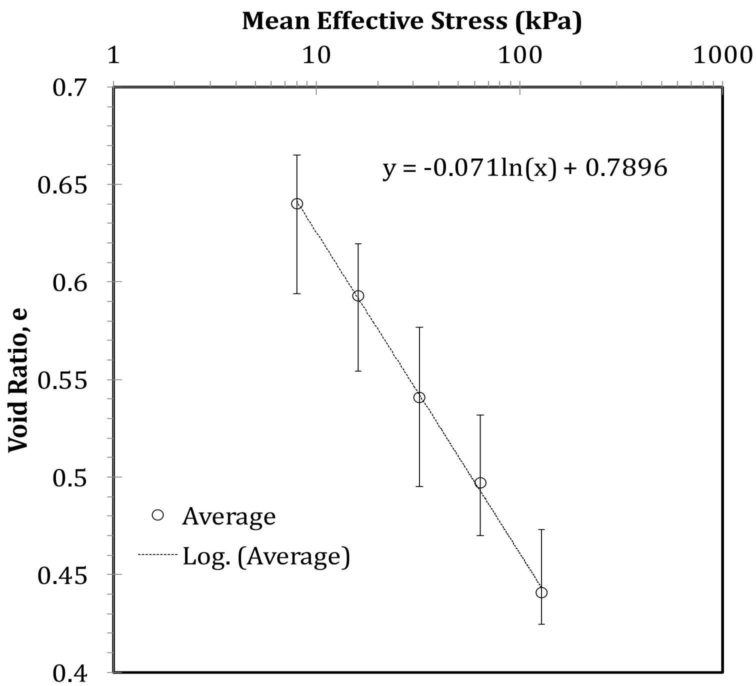

FIG. 4. Void Ratio vs. Mean Effective Stress (redrawn after Ruffing and Evans 2010)

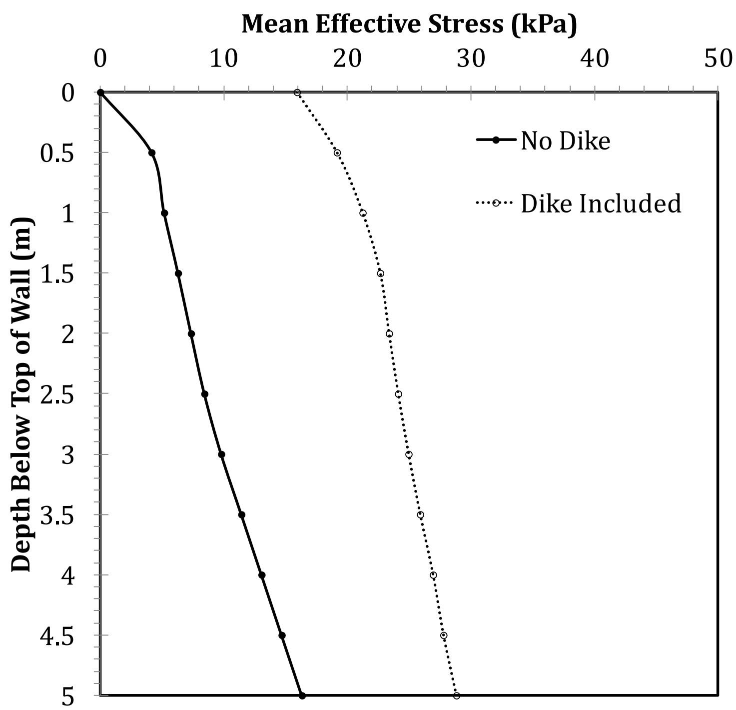

FIG. 5. Predicted *in situ* stress distribution within the backfill from MLSM

drying, as discussed further below.

For the condition where the soil has remained saturated (no drying), θ is equal to the porosity, *n*, which can be determined using the relationship between void ratio, e, and mean effective stress, σ'_{mean}. Ruffing and Evans (2010) investigated this relationship for the Birdsboro, PA slurry wall backfill using one-dimensional consolidation tests. The mean effective stress at each consolidation stage was calculated using Eq. 3:

$$\sigma'_{mean} = \frac{\sigma'_v + 2k_o\sigma'_v}{3} \qquad \textbf{(3)}$$

where σ'_v is the vertical effective stress and k_o is the at-rest lateral earth pressure coefficient (assumed to be 0.5). The assumed earth pressure coefficient was chosen based on an estimation of the backfill friction angle consistent with previous studies (Baxter et al 2005). The e-log $-\sigma'_{mean}$ curve for the backfill is shown in Fig. 4. The *in situ* mean effective stress distribution with depth in the wall also was calculated using Eq. 3, where σ'_v is given by the modified lateral squeezing model as described by Ruffing et al. (2010, 2011). The computed *in situ* mean stresses in the backfill before and after construction of the dike are shown in Fig. 5.

The predicted *in situ* mean effective stress distribution presented in Fig. 5 was used in conjunction with the e-log σ'_{mean} curve in Fig. 4 to estimate the *in situ* void ratio distribution in the backfill. The estimated void ratio distribution was then used in conjunction with the θ profiles in Fig. 3 to create degree of saturation (*S*) profiles for each monitoring event. These profiles are illustrated in Fig. 6. The data in Fig. 6 shows that the lowest *S* is at a depth of 1.8 m, just below the upstream water level in the adjacent formation. The *S* values at 3.7 and 4.3 m indicate that the wall is saturated, consistent with the presence of the water table at a depth of 3.5 m on the downstream side of the barrier.

Another useful way to examine the measured and computed data is directly in terms of θ rather than *S*. The measured θ values obtained from the TDR sensors are replotted in Fig. 7 along with predicted θ values

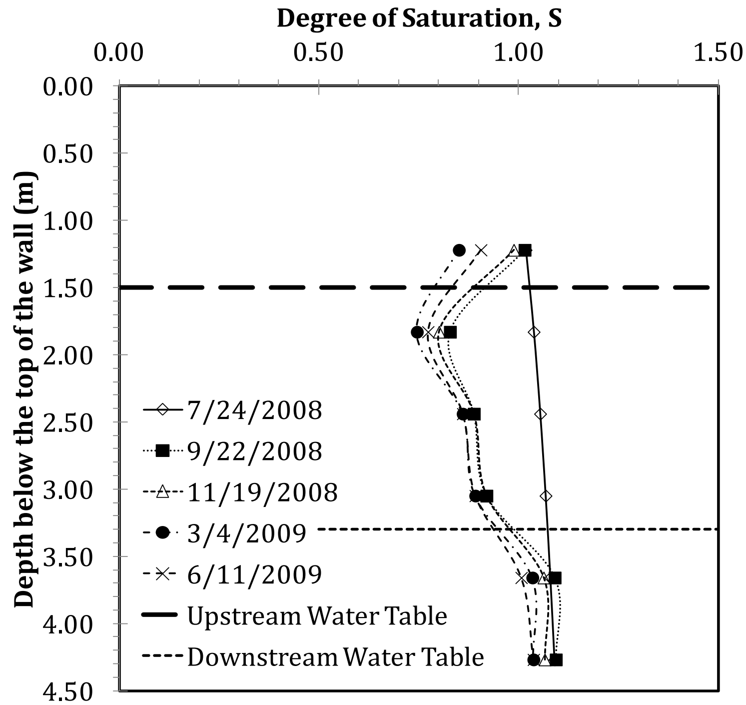

FIG. 6. Profiles of the calculated degree of saturation within the backfill

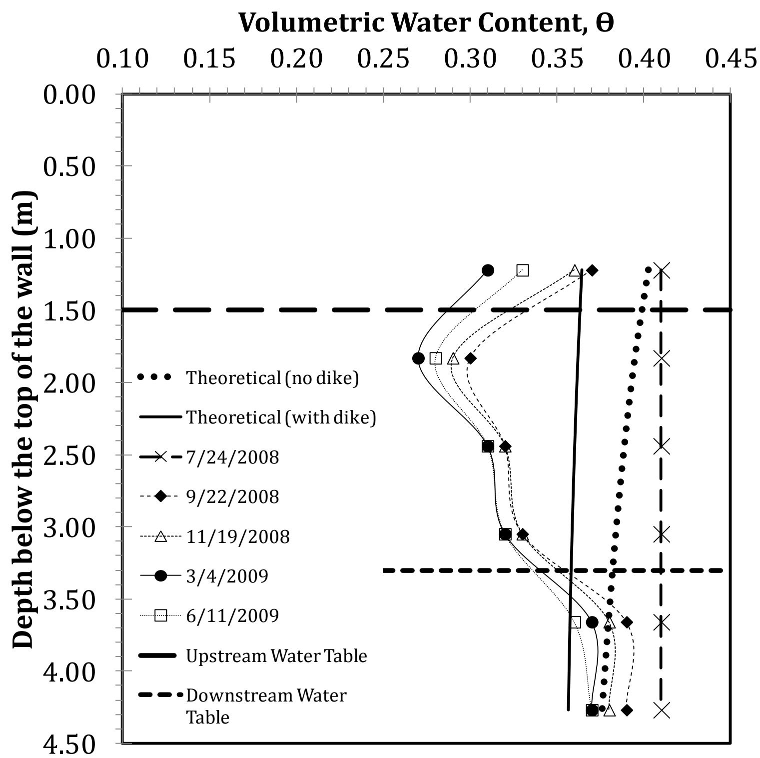

FIG. 7. Measured vs. Predicted Θ Profiles

calculated using the laboratory data in Fig. 4 and the predicted *in situ* mean effective stresses in Fig. 5, assuming that the backfill is fully saturated. Two observations become clear based on the results in Fig. 7. First, for the two probes located below the water table (i.e., depth = 3.7 m and 4.3 m), the decreases in θ are consistent with those predicted solely based on consolidation of the backfill due to the combination of self-weight and the dike surcharge loading (see Fig. 5). Second, changes in θ above the downstream water table are inconsistent with predictions based solely on consolidation. For these locations, in addition to moisture changes due to consolidation, it is postulated that moisture is wicked from the high moisture content backfill to the low moisture content soil adjacent the wall.. Finally, the data measured in the probe located at 1.2 m is likely influence by arching of the dike surcharge load over the trench resulting in a lower degree of consolidation at near surface locations and subsequently a higher θ.

CONCLUSIONS

Six time-domain reflectometry (TDR) sensors were successfully installed in a soil-bentonite slurry trench cutoff wall on the day of backfill placement and monitored for nearly one year. The data from the sensors revealed a time-dependent decrease in volumetric water content (θ) at all of the monitored depths within the wall. The decreases in θ at the two sensor locations below both the upstream and downstream water tables were consistent with consolidation of the backfill due to a combination of self-weight and the surcharge from an overlying dike. For these sensor locations, predicted values of θ based on the modified lateral squeezing model were reasonably consistent with the measured values of θ from the sensors. The sensors installed at shallower depths (i.e., above the adjacent water tables) indicated more substantial decreases in θ relative to those predicted based on consolidation alone, indicating that some drying of the backfill has occurred.

The results of this study are limited by the inherent assumptions used to analyze the sensor data. For example, an inherent assumption in the analysis is that the correction factors to account for potential deviation of the sensor prongs from a parallel orientation are valid. Also, the correction factors, determined for each sensor in an unconsolidated, fully saturated environment, are assumed to remain constant after consolidation (and potentially drying) had taken place. Intrusive field studies (i.e., borings) would be required to verify the accuracy of the moisture profiles given by the TDR sensors. Future studies also should focus on improved methods for installing TDR sensors in freshly placed backfill as well as on studying moisture changes in deeper walls constructed primarily below the water table.

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