Evaluations of lateral earth pressure in a soil-bentonite slurry trench cutoff wall

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ABSTRACT
Soil bentonite (SB) slurry trench cutoff walls are widely used to control the movement of ground water and subsurface contaminants. This paper presents findings from *in situ* tests conducted on an SB wall using the Marchetti Dilatometer Test (DMT). This paper also describes a modified lateral squeezing model that accounts for loading associated with a dike built shortly after construction of the wall was completed. Data from the DMT were obtained during slurry wall construction as well as three, six, and nine months after construction to evaluate changes in the lateral stress state with time. The dilatometer provided a unique opportunity for relatively direct measurement of the *in situ* horizontal earth pressure. The DMT was conducted in both perpendicular and parallel orientations (relative to the trench line) to investigate stress anisotropy within the wall. Dilatometer data revealed modest differences in the lateral stress state as a function of both orientation and time. The transverse stresses are slightly greater than the longitudinal stresses. Both transverse and longitudinal stresses increase with time. The lateral stresses computed from the DMT results compared favourably with those predicted by the modified lateral squeezing model that was adapted to include the influence of the dike.

RÉSUMÉ
Sol bentonite (SB) murs de boue des tranchées de coupure sont largement utilisés pour contrôler le mouvement des eaux souterraines et des contaminants souterrains. Ce document présente les résultats d'essais in situ réalisés sur un mur en utilisant le SB Marchetti Dilatomètre Test (DMT). Ce document décrit également un modèle modifié latérales compression qui tient compte de charge associée à une digue construite peu après la construction du mur a été achevée. Les données de la DMT ont été obtenus au cours de la construction du mur suspension ainsi que de trois, six et neuf mois après la construction pour évaluer les changements dans l'état de contrainte latérale avec le temps. le dilatomètre fourni une occasion unique pour la mesure relativement directe de la pression dans la terre situ horizontale. La DMT a été menée dans les deux orientations perpendiculaires et parallèles (par rapport à la ligne de tranchée) pour enquêter sur l'anisotropie des contraintes dans la paroi. Dilatomètre données a révélé des différences modestes dans l'état de contrainte latérale comme une fonction à la fois l'orientation et l'heure. Les contraintes transversales sont légèrement supérieures aux contraintes longitudinales. Les deux transversales et longitudinales souligne augmenter avec le temps. Les contraintes latérales calculées à partir des résultats DMT se compare favorablement avec ceux prédits par le modèle modifié compression latérale qui a été adapté inclus l'influence de la digue.

1 INTRODUCTION

Soil bentonite (SB) slurry trench cutoff walls have been widely employed as a means of groundwater and contaminant control (Evans 1993, 1994). The permeability of SB backfill is strongly dependent on the effective confining stress within the backfill, even at the low stress ranges commonly observed in these walls (Evans et al. 1995, Ruffing and Evans. 2010). This relationship between permeability and stress necessitates an understanding of the state of stress in SB cutoff walls, including changes with time, depth, and orientation. Modeling of the state of stress has included considerations of arching (Evans et al, 1995), lateral squeezing (Filz 1996), and lateral squeezing modified to include nonlinear stress-strain behavior (Ruffing et al. 2010). Despite the need for understanding how the stress develops *in situ,* the research effort devoted to these walls has been largely focused in the laboratory (National Research Council 2007).

In the summer of 2008, researchers from Bucknell University performed *in situ* testing on a SB wall located in southeastern Pennsylvania. The focus of this paper is the presentation and analysis of Marchetti Dilatometer Test (DMT) results in terms of lateral pressure and the inclusion of a dike surcharge into the lateral squeezing model. The use of vane shear, cone penetrometer, and DMT results to approximate the shear strength within the wall was described previously (Ruffing and Evans 2010). This paper reinterprets the DMT data to estimate the effective horizontal pressures within the wall. The paper provides a comparison of these pressures with those predicted using a modified lateral squeezing model that accounts for the influence of surcharge load from a dike built approximately six weeks after the cutoff wall was constructed.

2 CUTOFF WALL CONSTRUCTION

In order to control site flooding at a municipal wastewater treatment facility built in a floodplain, a flood control dike over the top of a SB vertical cutoff wall were designed and constructed. The SB wall was intended to limit inflow of groundwater such that wastewater tanks installed below grade do not become buoyant during flooding events of a nearby river. The wall was constructed under the technical guidance of Geo-Solutions Inc. and is approximately 350 m long and 4.5 m deep at its deepest point (about 1400 $m^{2)}$. The SB wall backfill was prepared by blending the excavated soils with bentonite-water slurry plus approximately one percent dry bentonite. The subsurface consisted of clayey silty sands and gravels. About one month after cutoff wall construction, a clay core dike was installed on top of the wall to limit surface water impacts at the facility. Prior to dike construction, the working platform was graded and a geotextile support was installed directly over the wall to limit embankment settlement. Figure 1 shows a cross-section of the completed dike and cutoff wall along with groundwater observations at t = 3, 6, and 9 months after wall construction. The groundwater levels in the monitoring wells installed upgradient and downgradient of the wall indicate that the wall is behaving as intended, i.e. as a barrier to groundwater flow.

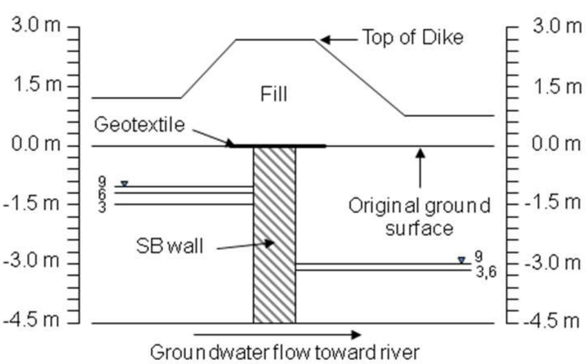

Figure 1 Cross-section of flood control dike and cutoff wall, along with measured groundwater levels at t = 3, 6, and 9 months after wall construction (redrawn after Ruffing 2009).

3 *IN SITU* TESTING METHODS AND DATA INTERPRETATION

The subsurface investigation of the cutoff wall was performed using Bucknell University's track-mounted drilling rig (see Figure 2) and *in situ* testing equipment including the DMT (Marchetti, 1980). The DMT protocol and data analysis closely followed the methods in Schmertmann (1988) combined with those presented in ASTM D6635-01. The dilatometer control panel and blade are shown in Figure 3. The blade includes a thin, circular steel membrane and is connected to the control panel by a flexible tube containing a metal wire. The drill rod served as the electrical ground, thus requiring the control panel to be grounded to the drill rod.

Figure 2 Drilling rig used for cutoff wall testing

After the blade was pushed to the desired testing depth, compressed air was used to expand the steel membrane on the dilatometer blade. Pressure readings were recorded (1) when the air pressure just started to move the membrane outward (the *A* reading) and (2) after 1.0 mm of further lateral displacement measured at the center of the membrane (the *B* reading). The air pressure was then dialed down to allow the membrane to be pushed back toward the blade by the lateral earth pressure. The pressure at which the blade returned a distance of 1.0 mm was recorded (the *C* reading). All three readings are influenced by disturbance effects associated with the blade insertion. Calibration factors, ΔA and ΔB, were determined prior to insertion in the ground. These calibration factors help to correct for the stiffness of the membrane. Deviation from zero on the gage was also recorded (Z_g). These corrections were then applied to the pressure readings recorded during the test, and the results were used to calculate the lateral earth pressure at the test depth (Schmertmann 1988).

Figure 3 Dilatometer control panel (left) and blade (right)

Lateral stress and pore water pressure within the cutoff wall were computed from the DMT data as follows:

$$p_o = 1.05(A - Z_g + \Delta A) - 0.05(B - Z_g + \Delta B) \qquad \text{Eq. 1}$$

$$p_2 = C - Z_g + \Delta A \qquad \text{Eq. 2}$$

where p_o represents the total lateral earth pressure and p_2 represents the pore water pressure (Schmertmann 1988). Values of the horizontal effective stress (σ'_h) were then calculated by subtraction, i.e.,

$\sigma'_h = p_o - p_2$ Eq. 3

The DMT was conducted with the blade oriented both parallel and perpendicular to the trench alignment, as illustrated schematically in Figure 4.

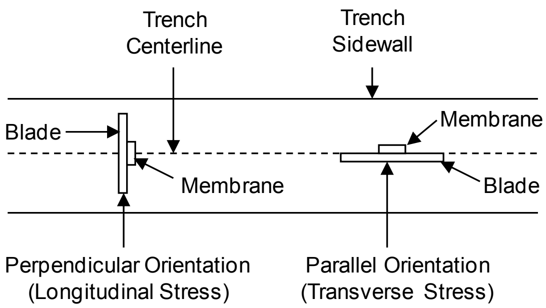

Figure 4 Longitudinal and transverse dilatometer orientations used in this study (plan view)

4 MODELING LATERAL STRESSES INCLUDING THE INFLUENCE OF THE DIKE

As noted previously, methods to estimate the state of stress within a SB cutoff wall have included consideration of arching, lateral squeezing, and modified lateral squeezing with nonlinear backfill compressibility. In this study, the influence of a dike constructed after the cutoff wall was complete was added to the modified lateral squeezing model presented by Ruffing et al. (2010). The modified lateral squeezing model balances lateral stresses between the backfill inside the trench and the formation soils outside of the trench and allows sidewall deformation as well as accounting for the stress-dependent nature of SB backfill compressibility. The additional stress caused by the placement of the dike was calculated using the methods presented in Murthy (2003) for an infinite strip load. The lateral earth pressure within the backfill must be equal to the lateral earth pressure in the adjacent formation in order to maintain lateral stress equilibrium. As a lower limit, the lateral pressure will be equal to that calculated using the modified lateral squeezing model plus the additional lateral load added from the dike. Specifically, the following equation was employed for predicting σ'_h at any depth z from the top of the wall:

$\sigma'_h(z) = \sigma'_{hm}(z) + \Delta\sigma_z K_a$ Eq. 4

where σ'_h is the horizontal effective stress in the backfill, σ'_{hm} is the horizontal effective stress from the modified lateral squeezing model, $\Delta\sigma_v$ is the change in vertical stress (outside the trench) due to influence of the dike, and K_a is the active earth pressure coefficient of the soil adjacent to the trench calculated assuming an effective friction angle of 25 degrees. Values of $\Delta\sigma_z$ were computed using influence factors (I) given by the Boussinesq stress distribution for an infinite strip load, as follows:

$\Delta\sigma_z = \gamma_{dike} H_{dike}(z)(I)$ Eq. 5

where γ_{dike} and H_{dike} represent the total unit weight and height of the dike, respectively. The dike properties and I values used for this analysis are shown in Figure 5. The dike influence factors were 1.0 at the top of the cutoff wall (z = 0) and 0.63 at the bottom of the deepest part of wall (z = 4.5 m).

Influence Factors (dike only):

Depth, z (m)	Influence Factor
0.0	1.00
0.5	0.98
1.0	0.96
1.5	0.91
2.0	0.88
2.5	0.84
3.0	0.80
3.5	0.75
4.0	0.67
4.5	0.63
5.0	0.50

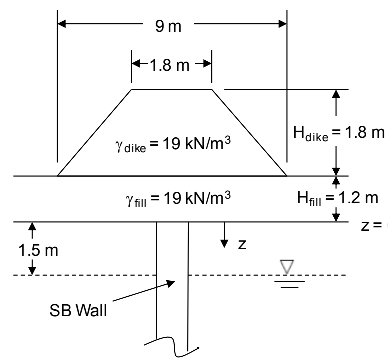

Figure 5. Dike dimensions and influence factors as a function of depth below the bottom of the dike

The computed $\Delta\sigma_z$ values from Eq. 5 were used in Eq. 4 to compute the predicted σ'_h as a function of depth within the cutoff wall. The predicted σ'_h values were then compared to the σ'_h values found from the dilatometer, as discussed in the next section of this paper.

5 RESULTS AND DISCUSSION

Figure 6 shows the σ'_h profile calculated from the dilatometer readings during construction (t = 0) and after the wall had aged (t = 3, 6, and 9 months). The predicted σ'_h profile (Eq. 4) is shown in Figure 6 for comparison. The influence of the dike was not included at t = 0 because the dike was not yet constructed. The measured σ'_h values may have been influenced somewhat by excess pore pressures generated during insertion of the dilatometer blade, but the comparison is valuable nonetheless. Due to field data collection errors, no t = 3 lateral stress determinations could be made.

An examination of Figure 6 reveals that horizontal stresses determined from the DMT data varies slightly with direction. The transverse stress (stress in a direction perpendicular to the alignment of the trench) is generally slightly greater than the longitudinal stress (stress in a direction parallel to the trench alignment). This finding is reasonable when the very low strength of the backfill is considered.

The DMT results in Figure 6 also reveal a modest gain in earth pressure from the time of construction and the data taken at 6 months. Given the presence of up to 50% fines in the formation soils, a vertical cut (with or without slurry or backfill) would exhibit undrained strength behavior immediately after excavation and transition to

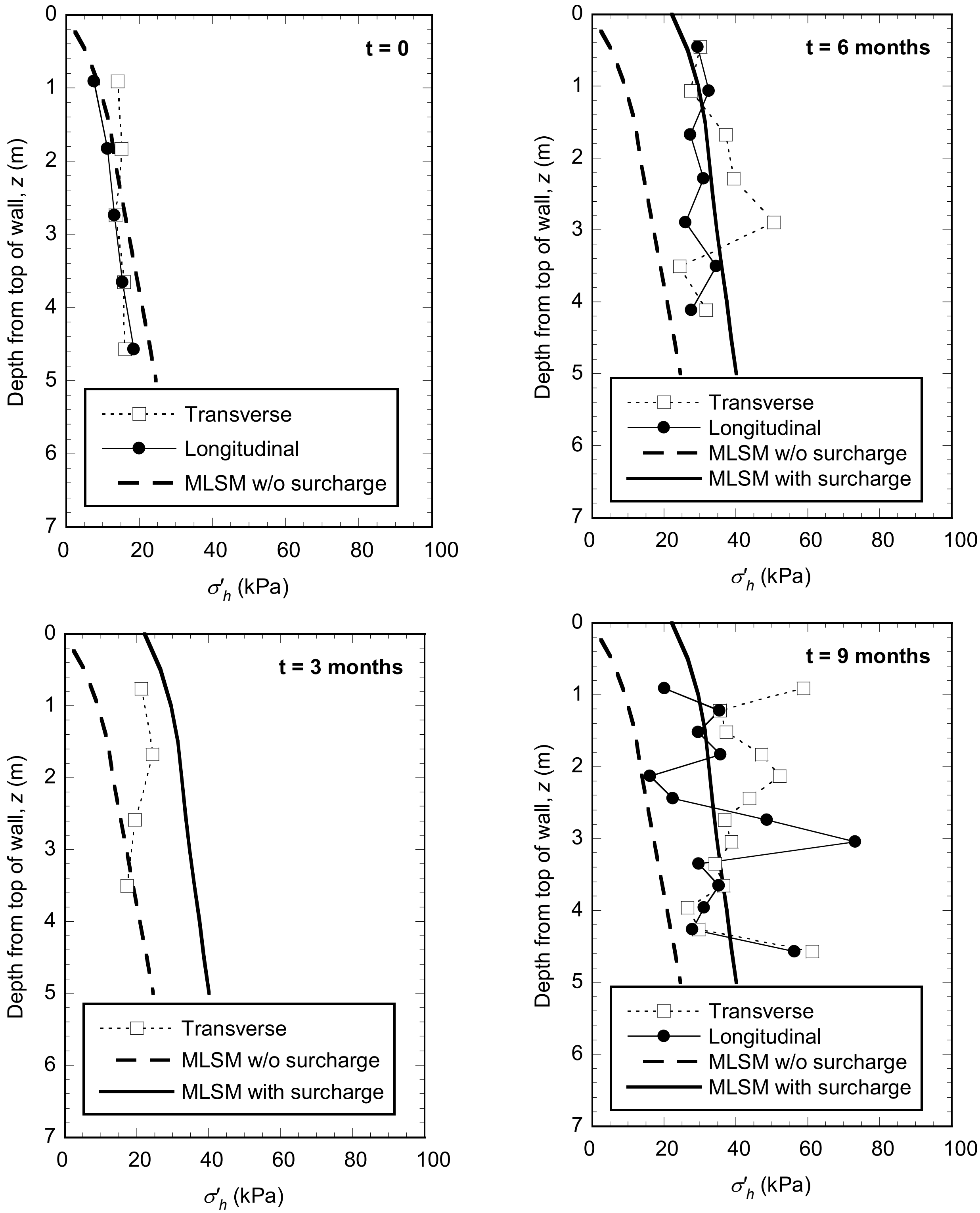

Figure 6 Comparison of measured (DMT) lateral stresses at t = 0, 3, 6, and 9 months after wall construction relative to lateral stresses predicted from modified lateral squeezing model (MLSM) with and without the dike surcharge.

drained strength behavior with time. Thus the lateral earth pressure applied to the backfill would be expected to increase with time and this expectation is consistent with the DMT results in Figure 6. An increase in lateral pressure after t = 0 would also be expected from the construction of the overlying site fill and dike. The increase in lateral pressure as determined from the DMT results is consistent with this expectation as well.

Figure 6 also demonstrates that σ'_h determined from the dilatometer at t = 6 months and t = 9 months correlates reasonably well with σ'_h predicted using the modified lateral squeezing method when the influence of the dike is included. At three months, the lateral squeezing model over-predicts the stresses indicating the system has not yet completed the transition from the undrained case to the drained case.

A discussion of the scatter in the DMT results, particularly at t = 9 months is warranted. The backfill was a well-graded material that included gravel and rock. Further, as is typical of SB cutoff wall construction, backfill was field blended along the trench with a bull dozer resulting in a heterogeneous backfill that includes variations in slurry content. Variation in DMT data is expected given the relatively small size of the dilatometer membrane coupled with the presence of rocks and/or pockets of higher or lower than average slurry content. There were other testing errors for the 3 month data in the longitudinal direction. Thus only the transverse results are shown in Figure 6. A statistical analysis of data variability is planned to quantitatively describe the observed differences/similarities in time and orientation.

6 SUMMARY AND CONCLUSIONS

A series of dilatometer tests were conducted in SB slurry wall backfill over time with the first data set collected during wall construction. Subsequent to wall completion, a dike was constructed over the wall that increased the vertical and horizontal stresses in the formation adjacent the cutoff wall. The additional lateral stresses in the formation added lateral stresses to the backfill. The study also found that the longitudinal stresses are slightly less than the transverse stresses. In addition, the DMT results revealed an increase in lateral pressure with time up to approximately 6 months. Analysis of the results found reasonable agreement between lateral stresses from the dilatometer tests and the predicted lateral stresses from a modified lateral squeezing model incorporating the dike surcharge.

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