Excess Pore Water Pressure Induced in the Foundation of a Tailings Dyke at Muskeg River Mine, Fort McMurray

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ABSTRACT
The External Tailings Facility dyke at the Muskeg River Mine north of Fort McMurray has been under construction since 2000. Data from piezometer installations within the tailings dyke foundation provide a unique opportunity to investigate the effect of staged construction on the generation and dissipation of excess pore water pressure within the foundation clayey units. In this study, pore water pressure generation data for the clayey facies of the foundation was compiled. Piezometric data were used to estimate the dissipation parameters for the clayey units at a selected zone of the foundation. Explanations were provided for spatial and temporal variations in the pore water pressure generation parameters.

RÉSUMÉ
La digue de l'Installation externe de rejets à la mine de la rivière Muskeg, au nord de Fort McMurray est en construction depuis 2000. Les données tirées des installations de piézomètres à l'intérieur de la fondation de la digue de rejets constituent une occasion exceptionnelle d'examiner l'effet de la construction par étapes sur la production et la dissipation de pression d'eau interstitielle excessive à l'intérieur des unités argileuses de la fondation. La présente étude a compilé les données de production de pression d'eau interstitielle pour le faciès argileux de la fondation. Les données piézométriques ont été utilisées pour estimer les paramètres de dissipation des unités argileuses d'une zone sélectionnée de la fondation. Des explications ont été fournies pour les variations spatiales et temporelles des paramètres de production de pression d'eau interstitielle.

1 INTRODUCTION

Shell Canada Energy (SCE) operates the Muskeg River Mine (MRM), an open pit oil sands mining and extraction facility, about 70 km north of Fort McMurray, Alberta. As by-product of the extraction, tailings are pumped from the extraction plant to the External Tailings Facility (ETF), a tailings impoundment.

The tailings placement is ongoing in the ETF using conventional upstream and centreline dyke construction methods in 2 m to 4 m dyke lifts. The dyke has a perimeter length of approximately 12 km. The current dyke height is a maximum of 54 m at the highest point around the dyke perimeter. The ETF dyke is divided into 20 cells, each 500 m to 700 m long. An aerial photo of the ETF is shown on Figure 1.

The dyke is founded on the McMurray Formation. The loads imposed by construction of the dyke create excess pore water pressure within the low permeable foundation units.

The Mud Flat (MF) and Tidal Flat Mud (TFM) facies of the McMurray Formation are medium to high plasticity clay layers in the foundation which typically control the stability of the dyke. Understanding the generation and dissipation process of excess pore water pressure within these layers is crucial to the dyke performance, design optimization and future design of the dykes founded on the McMurray Formation.

Figure 1. ETF tailings pond and analysis area.

The purpose of this paper is to show how the piezometric data has been used to improve estimates of the construction induced pore water pressure and dissipation rates within the TFM/MF clay layers in the foundation during the dyke construction. A transient finite element seepage model was used to estimate the coefficient of consolidation and permeability of the TFM/MF foundation layer.

2 SITE GEOLOGY

The ETF dyke foundation profile typically consists of (in descending order from the ground surface): Holocene deposits of muskeg, Pleistocene sand, Cretaceous McMurray Formation (oilsands), and Devonian Waterways Formation (limestone).

Muskeg has been stripped from the starter dyke foundation. At some locations a surficial veneer of Pleistocene sand is present above the McMurray Formation and directly underlines the dyke.

Clay size facies within the McMurray Formation dominate the foundation stability of the dyke. The McMurray Formation consists of the Upper, Middle and Lower Members. At the ETF site, the upper members of the McMurray Formation are progressively eroded to the south. The Lower McMurray Formation is relatively deep at this site and its effect on the foundation stability is limited for most of the dyke perimeter.

The Middle McMurray Member was deposited in a tidal/estuarine environment and is highly channelized and interbedded. The focus of this paper is the pore pressure response to loading of the Tidal Flat Mud (TFM) and Mud Flat (MF) facies within the Middle Member of the McMurray Formation. The Mud Flat (MF) facies is a massive, light to medium gray clay with infrequent (less than 10% of the layer thickness) beds or lenses of fine sand and silt. The Tidal Flat Mud (TFM) facies is similar to the MF, but with more frequent (10% to 30%) thin (millimeter scale) beds of fine sand and silt.

The TFM and MF clays are typically medium plastic. At this site, typical liquid limits for TFM range from 30% to 40% with a mean of 35%, while for MF range from 30% to 50% with a mean of 40%. The natural moisture content is typically near the plastic limit, indicating that the clays are heavily overconsolidated. A photograph of a thick bed of MF/TFM clay is shown in exposure in Figure 2. Fragments from a weathered block of MF clay are shown in Figure 3.

3 FOUNDATION PORE WATER PRESSURE EFFECTS ON STABILITY

3.1 Construction Induced Pore Water Pressures

Increasing pore pressures due to stress changes can result from an increase in the total normal stress and shear stress. In heavily overconsolidated clays such as those in the McMurray Formation, the pore pressure change resulting from an application of shear stress is typically near zero or negative for strains approaching failure. Therefore, in early stages of construction, the primary mechanism of pore pressure increase during construction is due to an increase in total normal stress. With the dyke construction and increasing stress level on the soil, the overconsolidation ratio is reduced and the pore pressure change resulting from an application of shear stress can be positive.

Figure 2. Exposure of Mud Flat / Tidal Flat Mud facies

Figure 3. Mud Flat clay

Staged construction uses a controlled rate of load application to increase the foundation stability of dams. After each stage of construction, dissipation of excess pore water pressures increases the factor of safety against a shear induced failure. Therefore, the most critical stability condition happens after each load application.

If loading occurs relatively slowly, the increase in pore pressure induced from the previous load increment can dissipate prior to the application of the next load increment. When more rapid loading occurs, relative to the time required for pore pressure dissipation, some or all of the pore pressure induced by the application of the previous load increment still remains within the soil when the pore pressure increases due to the following load increment. The dyke design must therefore account for the rate of loading and the rate of pore pressure dissipation. Controlling the rate of loading and therefore rate of stress induced excess pore water pressure generation is important in the general stability of the dyke during construction (Ladd 1986).

3.2 Foundation Pore Water Pressure in Design

In the construction of the ETF, effective stress strength parameters were used to characterize the strength of the foundation, which requires predictions of the pore water pressures induced during construction. A comprehensive network of piezometers in critical foundation clay facies and within the dyke was used to monitor the pore pressures, and confirm or update the design assumptions as construction progressed. Piezometers were installed in the foundation below the main dyke, as well as under the toe berms that were used to control deformations during construction of the dyke to the design elevation.

The dyke performance information was used to optimize the design for raises to the tailings dyke. The pore pressures in low-permeability foundation materials were predicted based on the pre-construction water table and the stress-induced excess pore pressure response extrapolated from the piezometric data at each zone.

The overburden weight, permeability of the clay layer, length of drainage path, hydraulic boundary conditions and rate of construction including construction stoppages all affect the pore pressure at each stage of the dyke raise. Because of interdependence of these factors, it is difficult to isolate the relative influence of any one factor on the development of construction pore pressures.

3.3 Representation of Induced Pore Pressures

Pore pressure coefficients are normally used to estimate the response of pore pressure within the low permeable material during construction. These coefficients estimate the excess pore pressure generation as a function of changes in total stress.

The pore pressure change (Δu) is characterized by Skempton's 'A' and 'B' parameters (Holtz and Kovacs, 1981), which relate changes in pore water pressure to changes in deviatoric and confining stress, respectively:

$$\Delta u=B[\Delta\sigma_3+A(\Delta\sigma_1-\Delta\sigma_3)] \quad [1]$$

Dividing through by $\Delta\sigma_1$ results in:

$$\Delta u/\Delta\sigma_1=B[\Delta\sigma_3/\Delta\sigma_1+A(1-\Delta\sigma_3/\Delta\sigma_1)] \quad [2]$$

The combined effect can be characterized by the parameter $\overline{B}$, which is defined:

$$\overline{B} = \Delta u/\Delta\sigma_1 \quad [3]$$

In equations [1] to [3]:

$\Delta\sigma_1$ and $\Delta\sigma_3$: changes in total maximum and minimum principal stresses from previous loading stage

Δu: change in pore water pressure from previous loading stage

A, B and $\overline{B}$: pore pressure coefficients

$\overline{B}$ is therefore a function of B (equal to 1 for saturated soils), A, and the stress ratio $\Delta\sigma_3/\Delta\sigma_1$. Prediction of the pore water pressure changes using the $\overline{B}$ parameter must therefore consider variations in the stress ratio and shear strain, since A is a function of shear strain.

The increment in the total major principal stress is generally not known unless numerical stress-deformation analyses are performed of the dam and foundation system. In the effective stress analysis of embankments the increment in total major principal stress is often assumed to approximately equal the increment in total vertical stress, so that $\overline{B}$ can be approximated as:

$$\overline{B} = \Delta u/\Delta\sigma_v \quad [4]$$

Where:

$\Delta\sigma_v$: change in vertical total stress

This approximation is reasonable for one-dimensional loading conditions such as are found far upstream of the crest of a tailings impoundment, but is increasingly inaccurate near the downstream toe of the dyke, where the major principal stress increment may be horizontal. For this reason, piezometers near the toe of the impoundment may record increases in pore water pressure that are greater than the weight of fill placed over the piezometer installation.

The construction period of the ETF spans several years, therefore part of the stress-induced pore pressures dissipate during construction. For an effective stress analysis of the dyke stability at the end of construction, the pore water pressure used in the analysis must reflect the total history of increases due to fill placement and dissipation between lifts. This is accounted for through the use of an "equivalent $\overline{B}$" or $\overline{B}_{eq}$, in which Δu is the total change in pore water pressure up to the time of interest, at the stage of dyke construction being analyzed, and $\Delta\sigma_v$ relates to the total vertical stress change since the start of construction. $\overline{B}_{eq}$ is not a material parameter, and depends on the rate of construction, dissipation time, stress ratio and magnitude of strain.

4 EXCESS PORE WATER PRESSURE WITHIN TFM/MF

4.1 TFM/MF Equivalent $\overline{B}$ Values

Pre-construction data showed that the original pore pressure within the foundation was close to a hydrostatic pressure distribution with the water table near the original ground surface.

A summary of the pore pressure response of the TFM and MF clays, characterized using the $\overline{B}_{eq}$ parameter, is listed in Table 1. The data were taken approximately 9 years after the start of construction when the dyke reached a crest height of 50 m.

Generally, the piezometers installed in the foundation beneath the toe berm present the highest $\overline{B}_{eq}$ during construction, due primarily to the higher loading rate with little time for pore pressure dissipation. There is, however, significant spatial variation in measured pore pressure response. As data were obtained during construction, the $\overline{B}_{eq}$ parameters were adjusted for each design section.

Table 1. TFM/MF Equivalent $\overline{B}$ Summary.

Parameter	All Piezometers in TFM/MF	Piezometers Beneath *	
		Toe Berm	Dyke
Maximum	1.44	1.44	0.82
90^{th} percentile	0.68	0.73	0.52
Mean	0.37	0.42	0.30
Median	0.34	0.38	0.25
Minimum	0.02	0.02	0.05
Standard Deviation	0.25	0.28	0.18
Number of Piezometers	124	70	54

* Beneath "Toe Berm" Piezometers are installed downstream of the starter dyke downstream crest and Beneath "Dyke" piezometers are installed upstream of the starter dyke downstream crest

4.2 TFM/MF Facies Piezometric Responses

Excess pore water pressure due to the dyke construction can be seen in the responses of piezometers within TFM/MF clay facies. Responses of the piezometers to the construction depend on their location and depths in the clay layer, with more rapid dissipation near the upper and lower boundaries of the clay layer.

Figure 4 presents a simplified cross section of the dyke at Cell 9 area (location shown on Figure 1). Locations of some of the boreholes with piezometer tips in the TFM/MF facies are shown on this section.

Figures 5 and 6 present the responses of four piezometers installed in boreholes ASE01-723 and ASE01-724. As seen in Figure 4, borehole ASE01-723 is close to the downstream toe of the starter dyke and borehole ASE01-724 is located approximately 40 m upstream compared to ASE01-723.

As shown in Figure 5, the piezometric head within the two piezometers in borehole ASE01-723 (i.e. P184 and P169) first rose to approximately elevation of 294 m due to the stress increase from starter dyke construction, and stabilized at this elevation. Before the toe berm construction at this section, the pore pressures at these piezometers were generally decreasing slowly with occasional small increases corresponding to dyke crest raises. The main increases happened during the toe berm construction with the addition of fill directly above the piezometers. Both piezometers at this location show a similar pattern of response to the dyke and toe berm construction.

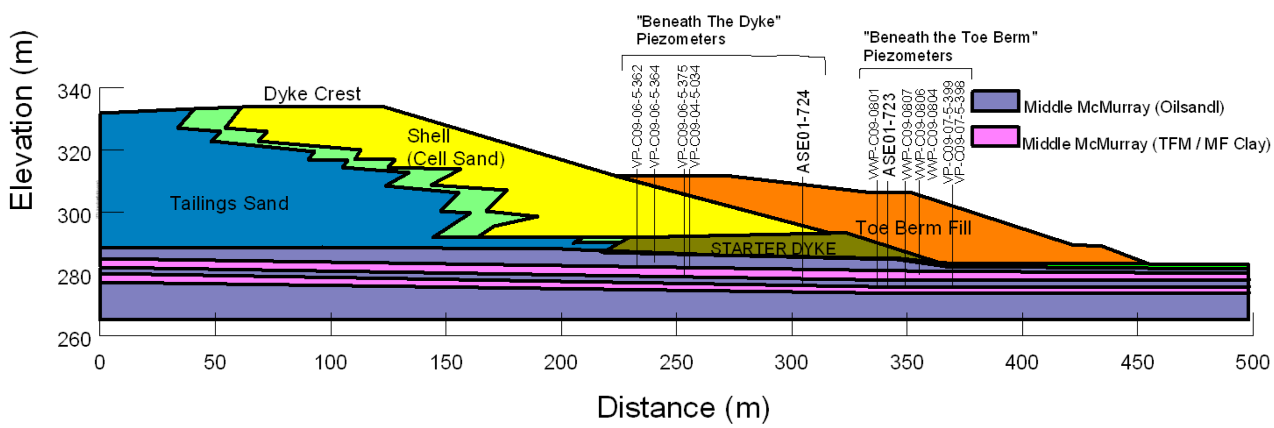

Figure 4. Simplified dyke section at Cell 9 showing borehole locations with piezometers in TFM/MF clay facies.

The responses of the piezometers installed in borehole ASE01-724 (i.e. P57254 and P1195) are slightly different from the ones in ASE01-723. These piezometers also show the main head increase during the time of direct fill placement above them (early stage of dyke raise and toe berm construction). However the piezometers in ASE01-724 show stronger responses to the dyke raise between April 2004 and February 2008 while there was no direct fill placement on top of them. The head increase during the dyke raise was greater in the shallower piezometer (P57254) compared to the deeper piezometer (P1195) at this location.

5 TFM AND MF PORE WATER PRESSURE DISSIPATION

As shown in Figures 5 and 6, some dissipation can be expected between the loading stages. Piezometers closer to the toe of the dyke responded to the initial construction of the dyke and construction of the toe berm along the dyke, but have not responded to more recent dyke construction which has occurred farther upstream from the location of the piezometers. Therefore, the effects of the initial dyke and toe berm construction can be isolated from the effects of the ongoing dyke construction, and the dissipation rates can be clearly observed, which is the case for piezometer ASE01-723, as shown on Figure 5. For piezometers located further upstream such as ASE01-724, the pore pressure dissipation from previous construction and increases due to further dyke construction are occurring simultaneously, and so the dissipation effects are difficult to isolate. Therefore, for estimation of the pore pressure dissipation within the TFM/MF clay facies, only piezometers under the toe berm were selected for further study.

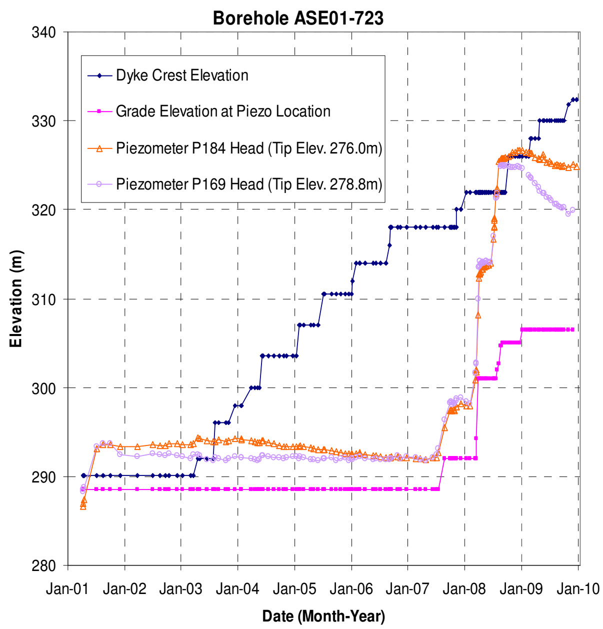

Figure 5. Pore pressure responses at ASE01-723.

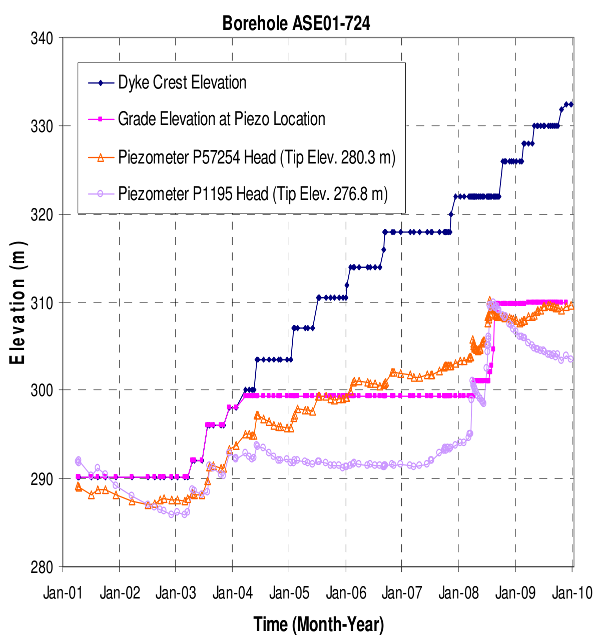

Figure 6. Pore pressure responses at ASE01-724.

5.1 Modeling Pore Water Pressure Dissipation

Figure 7 presents the geology and piezometer locations at borehole ASE01-723. Piezometers P184 and P169 are close to the mid-elevation of the TFM/MF clay layer.

A one-dimensional finite element model was constructed using program SEEP/W (GeoStudio 2007, GEO-SLOPE International Ltd.). The process of generation and dissipation of excess pore water pressure was modeled for the piezometers in borehole ASE-723 in the following steps:

- Step 1: Original condition without excess pore water pressure generation;
- Step 2: After piezometer installation and initial starter dyke fill placement, at the beginning of the dissipation process (in August 2001)
- Step 3: Dissipation process from the time of piezometer installation to the time before toe berm fill placement (from August 2001 to May 2007);
- Step 4: Increased pore pressure immediately after toe berm construction (from May 2007 to January 2009); and
- Step 5: Dissipation of pore water pressure after the toe berm fill placement to the current condition (from January 2009 to January 2010).

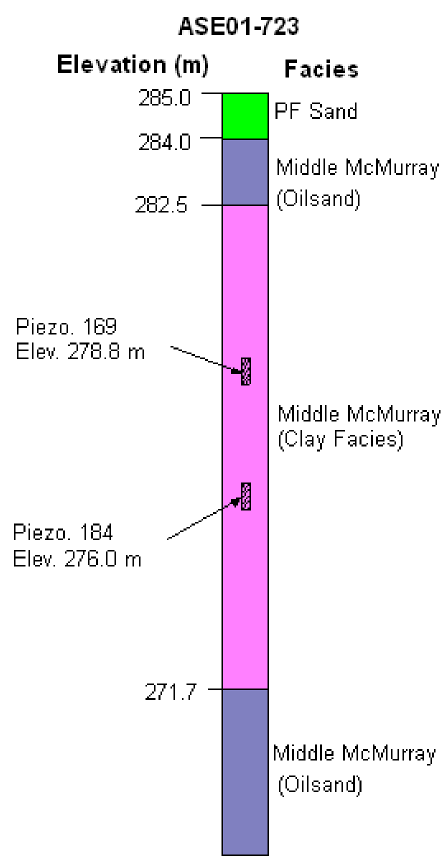

Figure 7. Foundation geology and piezometer locations at borehole ASE01-723.

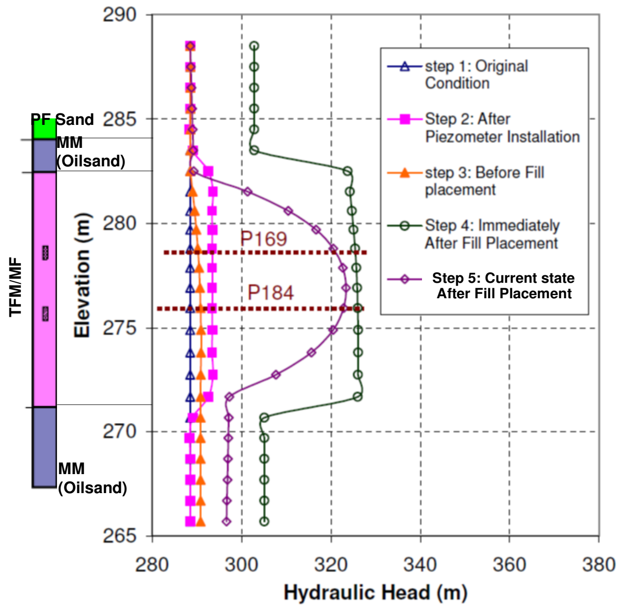

Figure 8. Modelled pore pressure in ASE01-723.

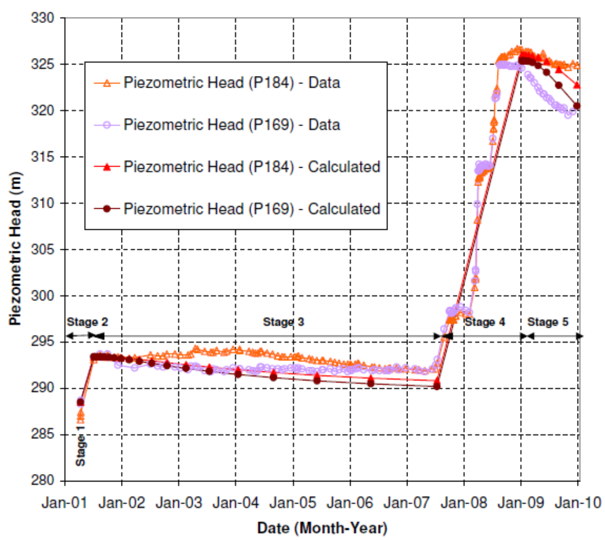

Figure 9. Comparison of measured and calculated heads in borehole ASE01-723.

The TFM/MF clay layer is sandwiched between Middle McMurray lean oilsand. The upper hydraulic boundary condition was selected as a constant head boundary condition with a head of 288.5 m. This is due to the presence of a permeable native sand layer close to the original ground surface. This layer causes a hydraulic connection to the water level within the dyke, which is maintained several metres above the original ground surface by internal drains in the dyke. The lower hydraulic boundary condition is more complicated. During construction, some excess pore pressure was produced within the general Middle McMurray facies (i.e. lean oilsand) beneath the TFM/MF clay facies. Data showed that the rate of generation of the excess pore pressure within this layer is approximately 30% less than the pore pressure generation within the TFM/MF clay facies.

The coefficient of consolidation (C_v) was changed in a trial and error process to match the result of transient seepage analysis model with the piezometric data. Figure 8 presents the hydraulic head variation in the model at some of the modeling steps. Figure 9 compares the predicted head at the piezometer locations in the model with the piezometric data. For the piezometers within borehole ASE01-723, the best fit to the data resulted in a C_v of 3.2 m^2/year.

A similar approach was used for the other piezometers in Cell 9 of the ETF. The resulting values of the coefficient of consolidation are listed in Table 2.

Table 2. Coefficient of Consolidation (C_V) values for piezometers within TFM/MF Clay facies in the toe of Cell 9.

Piezometer	TFM/MF Thickness (m)	Dissipation Period (Day)	C_V (m^2/y)
ASE01-723 (P184)	10.8	303	3.2
ASE01-723 (P169)	10.8	303	3.2
C09-07-5-398 (P61641)	5.9	489	1.5
C09-07-5-399 (P61859)	8.5	501	1.6
C09-0806 (P61683)	3.6	62	0.2
C09-0807 (P8263)	7.0	279	3.2
C09-0804 (P61687)	9	389	3.6
C09-0801 (P7613)	8.4	391	2.3

[1] Dissipation period were selected for the period with minimum construction activity

The calculated C_v values for the piezometers at Cell 9 are between 0.2 m^2/y and 3.6 m^2/y with a mean value of 2.4 m^2/y.

The coefficient of consolidation is related to the hydraulic conductivity of the soil through the equation:

$$K=c_v*m_v*\gamma_w \quad [5]$$

Where:

K: permeability (hydraulic conductivity) in the direction of seepage (primarily vertical in this case)

c_v: coefficient of consolidation

m_v: coefficient of volume compressibility (the reciprocal of the constrained modulus)

γ_w: is the unit weight of water.

In order to estimate the permeability of TFM/MF layers an estimation of m_v is required. Based on the results of undrained triaxial test for TFM/MF clays, m_v is estimated to be about 1×10^{-4} kPa^{-1}. The vertical hydraulic conductivity of the TFM/MF clay mass at the selected piezometer locations is calculated to be approximately 5×10^{-11} m/s to 1×10^{-10} m/s.

There are horizontal sandy layers interbedded within the TFM/MF facies. This causes an increase in hydraulic conductivity of these layers in horizontal direction. Also, these sand layers may cause hydraulic connection to higher permeability zones (such as sands channels incised into the TFM/MF facies) and faster pore pressure dissipation within TFM/MF layer. These effects are captured in the bulk vertical hydraulic conductivity calculated here based on the piezometric data.

6 EXCESS PORE WATER PRESSURE GENERATION IN TFM/MF

6.1 Construction Stages and TFM/MF Pore Pressure

Piezometers in boreholes ASE01-723 and ASE01-724 exemplified the effect of dyke and toe berm construction on the pore water pressure within the TFM/MF clay layer.

Based on the data from these piezometers, at the dyke toe, toe berm construction caused an increase in the pore pressure within the TFM/MF layer. Piezometers upstream of the starter dyke crest (e.g. ASE01-723) show more pore pressure increase in the early stages of the dyke raise. With further dyke raises the increase in the pore pressure due to this construction is lessened. The same pattern but with a weaker response can be seen in the piezometers at the toe, such as ASE01-724. The piezometer responses to the dyke construction can not be explained only by the vertical stress increases from direct fill placement above the piezometers.

6.2 Pore Water Pressure Response Coefficients

For the limit equilibrium stability analyses used in the dyke design, the pore pressures were represented using $\overline{B}_{eq}$. A limitation of this approach occurs in the simplification between equations [3] and [4]. During the initial dyke construction, fill placed directly over a piezometer near the dyke toe will result in a change in vertical total stress ($\Delta\sigma_v$) and the pore pressure response may be estimated using equation [4]. As the dyke construction progresses higher and fill is placed further upstream but not directly overlying the piezometer, for those lifts $\Delta\sigma_v=0$. However, the upstream load still causes a stress increment at the location of the piezometer, though in this case, the major principal stress increment ($\Delta\sigma_1$) is horizontal. The pore pressure change in this case should be estimated using equation [3]. For the case of Cell 9, a further change in the direction of the principal stress increment occurred when the toe berm was constructed, and the major principal stress increment was vertical again.

A finite difference stress analyses was performed to examine the directions of the principal stresses and the principal stress increments during construction. These analyses confirmed that the direction of the principal stresses changes from the dyke crest to the toe. During the staged construction, the direction of principal stresses rotates. Figure 10 presents the direction of the maximum principal stress at the location of piezometer P169 in borehole ASE01-723. The rotation of the principal stresses as the toe berm is constructed is evident on this figure.

This complex condition, together with pore pressure dissipation between lifts, causes changes in the $\overline{B}_{eq}$ values during construction. Figure 11 shows changes in $\overline{B}_{eq}$ with dyke and toe berm construction. Based on piezometric data, the $\overline{B}_{eq}$ for piezometer P169 changes between 0.49 and 1.18 while the $\overline{B}_{eq}$ for piezometer P184 changes between 0.61 and 1.03 for the period shown in Figure 11.

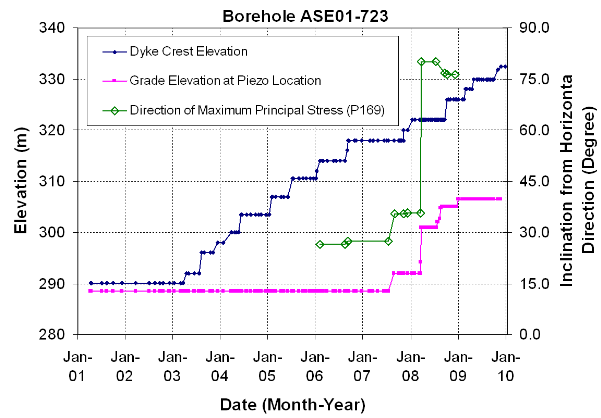

Figure 10. Changes in the maximum principal stress direction at piezometer P169 in ASE01-723.

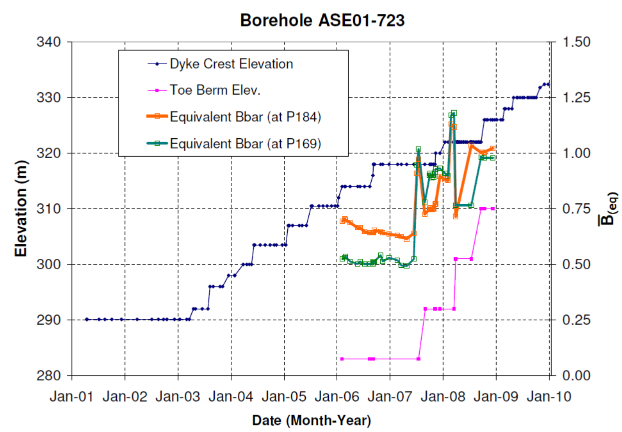

Figure 11. Change of equivalent $\overline{B}$ ($\overline{B}_{eq}$) with dyke and toe berm raise for piezometers in borehole ASE01-723

7 CONCLUSIONS

Piezometric data from piezometers within TFM/MF clay facies in ETF shows that excess pore water pressure was generated in the foundation clays by direct loading as well as loading further upstream due to dyke raises. Direct fill placement on the piezometers beneath the toe berm generated the largest excess pore pressure. Pore pressures are also generated by stress transfer in the foundation from fill that is not directly placed over a piezometer. Piezometers installed in critical clay facies at the toe of the dyke show dissipation of the excess pore water pressure after each stage of loading (Figure 5).

Use of $\overline{B}_{eq}$ greatly simplified the calculation of the excess pore water pressure generation for use in limit equilibrium stability models. The pore pressure parameter $\overline{B}_{eq}$ that is commonly used in embankment designs is not a material parameter, and depends on the rate of construction, dissipation time, stress ratio and magnitude of strain. The use of $\overline{B}_{eq}$ to estimate the pore water pressure within the foundation must account for spatial and temporal variations in this parameter.

Spatial variation in $\overline{B}_{eq}$ is due to non-vertical stress changes during the dyke crest raise, variation in the permeability of the foundation, and drainage conditions. Temporal variation in $\overline{B}_{eq}$ is due to dissipation of excess pore water pressure during the construction. Application of $\overline{B}_{eq}$ measured at one location or site should be used for other sites only with caution. Piezometric data show that the pore water pressure may dissipate if there is no loading or the load source is far from the piezometer location. Therefore, the $\overline{B}_{eq}$ values for piezometers in clay facies at the toe are expected to decrease with time during the dyke raise.

Based on the observed piezometric head dissipation at Cell 9 of the ETF, the coefficient of consolidation (c_v) of TFM/MF facies has been calculated to have a mean value of 2.4 m^2/y. The estimated mass vertical hydraulic conductivity based on the C_v values for piezometers in Cell 9 is between 5×10^{-11} m/s and 1×10^{-9} m/s.

8 ACKNOWLEDGMENTS

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