Embankment Design and Construction on Wick Drain Foundation Systems – A Case Study of the Installation Disturbance Effects for Clays on Highway 69/400 in Northern Ontario

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ABSTRACT
When estimating the rate of horizontal consolidation by radial drainage to a wick drain foundation, a value of the Smear Ratio (the ratio of the horizontal permeability of the undisturbed soil (k_h) to the permeability in the disturbed zone (k_s) adjacent to the wick drain caused by its installation) is required in the analysis. The smear ratio (k_h/k_s) is a difficult parameter to select for wick drain design as there is little to no guidance for the design engineer in literature in the way of empirical correlations based on field or laboratory test data. Based on accounts in published literature (none of which are for Eastern Canada), the smear ratio is considered site and/or area dependent and its value can range over an order of magnitude. In addition, its chosen value in wick drain analysis has a significant effect on the predicted rate of excess pore pressure dissipation and consolidation settlement. This paper presents the range of back-calculated values of smear ratio from several wick drain sites along the new Highway 69/400 alignment in Northern Ontario and proposes two empirical correlations for estimating the smear ratio a priori on future projects.

RÉSUMÉ
Lors de l'estimation du taux de consolidation horizontale par drainage radial vers un drain de carton, la valeur pour l'indice de remaniement « Smear Ratio » (c.à.d. le rapport de perméabilité horizontale du sol non-remanié (k_h) à la perméabilité dans la zone perturbée (k_s), adjacent au drain de carton, provoqué par son installation) est nécessaire à l'analyse. L'indice de remaniement « smear ratio » (k_h/k_s) est un paramètre difficile à définir car dans la littérature il existe peu de corrélations empiriques basées sur des essais sur le terrain ou en laboratoire pouvant guider l'ingénieur. D'après les articles publiés (dont aucun pour le Canada oriental) le taux de remaniement « smear ratio » varie en fonction du site et /ou de l'endroit et peu avoir une marge de variation au delà d'un ordre de grandeur. De plus, la valeur choisie dans l'analyse des drains de carton a un effet significatif sur le taux prévu de dissipation des pressions interstitielles, du tassement et de consolidation. Cet article présente les taux de remaniement « smear ratio » calculés à partir de l'analyse de plusieurs emplacements de drains de carton le long du nouvel alignement de la route transcanadienne 69/400 dans le nord de l'Ontario et propose deux corrélations empiriques pour estimer à priori le taux de remaniement « smear ratio » lors de projets futurs.

1 INTRODUCTION

Highway 69/400 is a major transportation route linking the southern portion of the province to Northern Ontario. The existing two-lane route was constructed in the 1950s and the volume of traffic on the road has increased steadily over the years leading to congestion, in particular in the summer months, over the past few decades. As a result, in order to reduce congestion and improve safety, the Ministry of Transportation, Ontario (MTO) and Transport Canada have committed significant funds to upgrade the route to a four-lane, controlled access roadway, with northbound and southbound lanes separated by a median. When completed, this 400-series highway will be a major transportation route extending from Highway 401 in Toronto to Sudbury in the north.

The current 152 km long section stretching from Parry Sound to Sudbury will include the construction of approximately 20 interchanges, over 100 bridge structures, 14 major river crossings, over 50 stream crossings and the construction of rock fill embankments over hundreds of swamps.

2 DESIGN OF EMBANKMENT SWAMP CROSSINGS ALONG HIGHWAY 69/400

Along the Highway 69/400 corridor, the swamp crossings can be up to 700 m long and contain peat/organic deposits up to 10 m deep, overlying soft clayey soils up to 30 m thick. Further, the new highway embankments crossing the swamp areas, generally comprised of rock fill, typically range in height from about 4 m to 10 m, but are up to as high as 26 m at some locations.

At most swamp crossings, where the combined thickness of organics and clayey soils is less than about 6 m to 8 m, full sub-excavation and replacement with rock fill is the usual foundation mitigation measure adopted to minimize the risks associated with embankment stability and long-term, post-construction settlement. However, where thicker and deeper deposits of soft soils are present, and/or in sections where sufficient quantities of rock fill cannot be made readily available to balance large cut/fill volumes that would be required in areas of deep sub-excavation and replacement, a wick drain foundation treatment is often adopted.

To date, wick drains have been successfully employed to increase the rate of consolidation (i.e. strength gain and settlement) at about ten of the swamp crossings on the Highway 69/400 alignment. At these swamp crossings, wick drains have been utilized with and without staged embankment construction, surcharging and toe berms, depending on the design embankment height, consistency (i.e. softness) and creep characteristics of the clayey soils. It is estimated that, so far, more than two million linear metres of wick drains have been installed.

The scale of the Highway 69/400 Four-Laning project and the numerous sites employing wick drain foundations provides a unique opportunity as a learning tool to investigate and refine some of the unknowns associated with wick drain design for sites in eastern Canada and in particular in Northern Ontario.

3 WICK DRAIN DESIGN

The design of a wick drain foundation system is based primarily on prediction of the rate of dissipation of excess pore pressure, by radial seepage, to vertical drains. The most widely used, analytical solution to this problem is that proposed by Barron (1948) which was developed for sand drains. The original theory by Barron was based on the assumptions of infinite permeability in the vertical drain (i.e. no drain or well resistance) as well as no adverse effects on soil permeability and/or consolidation properties due to drain installation (i.e. no disturbance or smear effects).

In the 1970s, as a result of large expansions in the geosynthetics industry, band shaped, prefabricated vertical drains (PVDs) or 'wick drains' that combine a geotextile filter wrapped around a thin geosynthetic core were developed and gradually became more widely used than sand drains. As a result, Hansbo (1979) modified the original solutions by Barron in order to consider the thin, rectangular cross-section of the geosynthetic wick drain and to include consideration of installation disturbance and drain resistance on the rate of pore pressure dissipation to the drains.

3.1 Installation Disturbance

The most common form of geosynthetic wick drain installation is a displacement method utilizing a steel mandrel to force its way into the soft soils and make room for the strip drain. This installation process causes disturbance and remoulding of the clay in the immediate vicinity of the mandrel thereby reducing the permeability of the soil in an area surrounding the drain. This problem, known as the 'smear effect', reduces the rate of infiltration of the dissipating excess pore water pressure into the wick drain. In fact, some researchers have shown that the smear effect results in a theoretical limit of how closely spaced the wick drains can be installed and still improve the overall rate of consolidation.

The amount of soil disturbance and the extent of the smear zone depend mostly on the size and shape of the cross-sectional area of the mandrel used for the installation but is also a function of the properties of the soils.

For a suitable mandrel size to have the least effect on soil disturbance, Akagi (1994) notes that the cross section of the mandrel must be minimized while still maintaining an adequate stiffness to overcome installation resistance, and providing sufficient space for the wick drain not to be structurally damaged or subjected to excessive friction upon withdraw of the mandrel.

When assessing the effects of the installation disturbance (or smear zone), it is both the diameter of the smear zone as well as the change in permeability of the soil in the smear zone in relation to that of the adjacent soil (or smear ratio – k_h/k_s) that must be considered.

3.2 Diameter of Smear Zone

The diameter of the disturbed zone or smear zone (d_s) is included in the solution by Hansbo (1979) as part of the consideration of installation disturbance effects. Numerous studies have been carried out to estimate the diameter of the smear zone (d_s) in relation to the diameter (equiv.) of the installation mandrel (dm). The results of some of these studies, based on laboratory tests, numerical analysis and back analysis from case records are summarized in Table 1.

Table 1. Summary of Diameter of Smear Zone.

d_s:d_m	Reference	Remarks
$d_s = 2d_m$	Hansbo (1981)	Review of case studies
$d_s = (2.5\text{ to }3)d_m$	FHWA (1986)	Review of literature
$d_s = (1.6\text{ to }4)d_m$	Onoue et al. (1991)	From test interpretation
$d_s = 2d_m$	Bergado et al. (1993)	Back analysis of field measurements
$d_s = (2\text{ to }3)d_m$	Miura et al. (1993)	Experimental study
$d_s = (2\text{ to }4)d_m$	Mesri et al. (1994)	From case studies of pile installation disturbance
$d_s = (4\text{ to }5)d_m$	Indraratna & Redana (1997)	Laboratory study
$d_s = (2\text{ to }3)d_m$	Chai & Miura (1999)	Laboratory and field study
$d_s = (1.6\text{ to }4)d_m$	Hird & Moseley (2000)	Laboratory study
$d_s = 4d_m$	Xiao (2002)	Laboratory study
$d_s = (3\text{ to }4)d_m$	Indraratna et al. (2007)	Numerical analysis and laboratory study

Based on the above, the ratio of d_s/d_m may range from about 1.5 to 5 with an average value of about 3.

However, Indraratna et al. (2007) note that from the results of the large scale laboratory testing study by Xiao (2002), based on the extent of the zone of excess pore pressure development around the mandrel as measured in fully instrumented 1 m diameter consolidation tanks, it is possible that in some cases the disturbed zone around the mandrel may be even greater than 4 or 5.

As a way of assessing the effect of the diameter of the smear zone (d_s) on the estimated rate of horizontal consolidation, a series of analyses have been carried out by the authors using the solution by Hansbo (1979) for radial consolidation to a wick drain. In the analysis, the typical parameters for the size of wick drain, installation mandrel and clays in Northern Ontario have been assumed as summarized in Table 2.

Table 2. Parameters for Wick Drain Sensitivity Analysis.

Parameter	Value
Installation Pattern	Triangular
Drain Spacing	1.5 m
Wick Drain Dimensions	100 mm x 3.6 mm
Mandrel Dimensions	125 mm x 50 mm
Discharge Capacity of Wick Drain	>150 m^3/year
Initial Effective Drain Length	10 m
Coefficient of Consolidation (c_v)	5.0 x 10^{-3} cm^2/s
Ratio of c_h/c_v	2
Coefficient of Compressibility (m_v)	1.0 x 10^{-3} kPa^{-1}

The results of the analysis for values of the ratio of the diameter of the smear zone to the diameter of the mandrel (d_s/d_m) varying from 1 to 10, for different values of smear ratio (k_h/k_s), are shown on Figure 1.

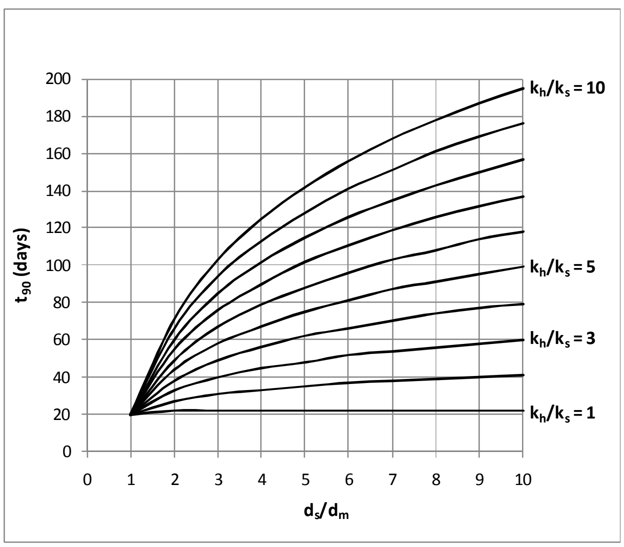

Figure 1. Effect of Diameter of Smear Zone (d_s) on Time for 90% Horizontal Consolidation

It can be seen on the above figure that for values of d_s/d_m greater than about 3, which is the average of the values recommended in literature as shown in Table 1, the effect on the estimated time to reach 90% horizontal consolidation (t_{90}) is modest, especially for low values of smear ratio (k_h/k_s). For example, for k_h/k_s = 3, increasing d_s/d_m from 3 to 5 will result in about a 20% increase in the estimate value of t_{90}.

3.3 Smear Ratio

Since remoulding of the soil as a result of disturbance during wick drain installation leads to a decrease in the coefficient of consolidation in an area immediately surrounding the drain and thereby to a delay in the consolidation process (Hansbo, 1979), this phenomenon has to be considered and accounted for in the radial consolidation analysis.

The effect of the reduced permeability of the soil within the disturbed zone adjacent to the wick drain is also included in the solution by Hansbo (1979) in the form of a ratio. The 'smear ratio' is defined as the ratio of the horizontal permeability of the undisturbed soils (beyond the smear zone) to the permeability of the soil within the disturbed zone or smear zone (k_h/k_s).

It is generally accepted that the value of the smear ratio is a difficult parameter to estimate for wick drain design. Hansbo (1979) notes that the value of the smear ratio is, "*more or less open to discussion*". FHWA (1986) notes that, "*very little published guidance is available to the design engineer.*"

Some researchers have carried out studies in an attempt to estimate the value of smear ratio for a particular site or type of clay. These studies have typically been based on back analysis from field monitoring data, although some are based on large scale laboratory testing. The estimated values of permeability (or smear) ratio from several of these studies are summarized in Table 3.

Table 3. Summary of Permeability Ratio in Smear Zone.

k_h / k_s	Reference	Remarks
k_h / k_s= 3	Hansbo (1981)	Review of case studies
k_h / k_s= 1 to 5	FHWA (1986)	Review of literature
k_h / k_s= 3	Onoue et al. (1991)	From test interpretation
k_h / k_s= 1 to 10	Mesri and Lo (1991)	Based on experience (all clays)
k_h / k_s= 2 to 5	Mesri and Lo (1991)	Based on experience (most lacustrine clays and silts)
k_h / k_s= 2 to 4	Crawford et al. (1992)	Back analysis of field measurements
k_h / k_s= 10	Bergado et al. (1993)	Back analysis of field measurements
k_h / k_s= 3 to 6	Almeida et al. (1993)	Based on experience
k_h / k_s= 3	Hird & Moseley (2000)	Laboratory study
k_h / k_s= 1.3	Xiao (2002)	Laboratory study
k_h / k_s= 3 to 4	Rankine et al. (2008)	Back analysis of field measurements

Based on the above, for the sites and/or types of clay soils investigated, the smear ratio (k_h/k_s) may range from as low as about 1 to as high as 10. The average of the above range of data is about 4. However, as noted in FHWA (1986), the smear ratio can be expected to vary with soil sensitivity and the presence or absence of soil macrofabric. As such, the value of the smear ratio should be a site or at least area specific parameter depending on the origin and genesis of the clayey soils. In Canada, there is a paucity of research that has been carried out to assess what value(s) of smear ratio may be applicable for the different clays in different regions. In fact, in Table 3 above, only the work by Crawford et al. (1992) is for a site in western Canada.

In order to assess the effect of the smear ratio (k_h/k_s) on the estimated rate of horizontal consolidation, a series of analyses have been carried out by the authors using the solution by Hansbo (1979) for radial consolidation to a wick drain. In the analysis, the same parameters employed previously and summarized in Table 2 have been utilized.

The results of the analysis for values of the smear ratio varying from 1 to 10, for different values of the diameter of the smear zone to the diameter of the mandrel (d_s/d_m), are shown on Figure 2.

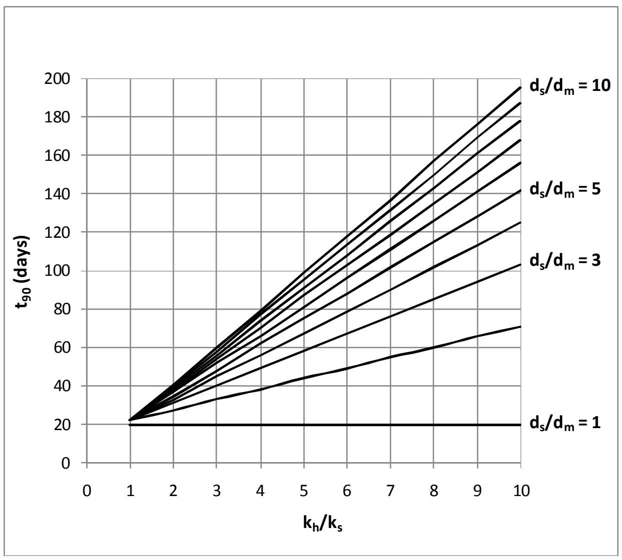

Figure 2. Effect of Smear Ratio (k_h/k_s) on Time for 90% Horizontal Consolidation

It can be seen on the above figure that except for cases where a very low value of d_s/d_m is assumed (i.e. $d_s/d_m = 1$), the value of the smear ratio (k_h/k_s) has a significant effect on the estimated time to reach 90% consolidation (t_{90}). For example, for $d_s/d_m = 3$, increasing k_h/k_s from 3 to 5 will result in about a 50% increase in the calculated value of t_{90}.

3.4 Discussion

Based on the preceding sections, it would seem that for design, the selection of the value representing the extent of the disturbed (or smear) zone (d_s/d_m) is somewhat less critical. The range of typical values of d_s/d_m is smaller and its effect on the estimated rate of consolidation is modest. In contrast, the smear ratio (k_h/k_s) is more site specific, has a wider range of possible values, a larger effect on the estimated rate of consolidation and is therefore more critical to the analysis. The following sections will focus on the value(s) of smear ratio applicable for the design of wick drain foundations in the soft to firm clayey soils below swamps in Northern Ontario.

4 METHODS OF ANALYSIS

As noted previously, wick drain foundation systems have been successfully designed and installed at dozens of swamp crossings along the new Highway 69/400 alignment. To date, Golder Associates Ltd. (Golder) and Thurber Engineering Ltd. (Thurber) have carried out the majority of the wick drain design for these sites.

At Golder, wick drain design has been undertaken using a variety of different methods depending on the complexity of the site conditions (i.e. depth and softness of the clayey soils, height of the embankment and concerns over stability and/or requirements for construction in stages). These methods have generally included:

- 1-D analysis (in a spreadsheet) using the simplified Skempton (1954) B-Bar method to estimate excess pore pressures and the Hansbo (1979) analytical solution to estimate rate of radial consolidation;
- 2-D analysis (in a spreadsheet) considering the influence of the geometry of the embankment section, using Poulos and Davis (1974) to estimate changes in stress and principal stress ratio in a 2-D field below the embankment, and Skempton (1954) to estimate changes in pore pressure in the 2-D field. Hansbo (1979) analytical solution is then used to estimate rate of radial consolidation; and,
- 2-D numerical, finite difference analysis (using FLAC) modelling the full embankment cross-section and foundation soils including drainage elements representing wick drain 'walls' (using a plane strain matching technique to simulate the axi-symmetric radial drainage solution, Hird et al. (1995)).

For the wick drain swamp crossing areas designed by Golder and discussed in the section below, the 2-D spreadsheet analysis method was employed. However, all subsequent back analysis to assess the smear ratio (as discussed in Section 6) only required use of the 1-D analysis method to consider the response of a single point.

5 WICK DRAIN DESIGN AT SWAMP CROSSINGS ALONG THE NEW HIGHWAY 69/400

In 2005, Golder was the foundation consultant for the detail design of an approximately 9 km long section of the new Highway 69/400 four-laning alignment south of Sudbury, Ontario between Highway 537 and Gladu Road in the Township of Dill. The project included the design of new twin embankment sections over eight swamp areas. For five of the eight swamps, a wick drain foundation combined with staged construction was selected as the preferred stability/settlement mitigation option. The detail wick drain design for the five swamp areas was carried out by Golder. For this paper, the results of the field monitoring data obtained from four (4) of the swamp areas, were initially considered.

In 2004, Peto MacCallum Ltd. (Peto) was the foundation consultant for the detail design of an approximately 11 km long section of the new Highway 69/400 four-laning alignment from 4 km south of Estaire, Ontario to Highway 537 in the Township of Burwash. The project included the design of several embankment swamp crossings, five of which were selected for a wick drain foundation treatment. The detail wick drain design for the swamp areas was carried out by Thurber. For this paper, the results of the field monitoring data collected from two (2) of the swamp areas, were considered.

For each of the wick drain swamps, a foundation monitoring system was designed to measure excess pore pressures and settlements during and following the construction. The monitoring systems included the installation of arrays of vibrating wire piezometers, vibrating wire settlement cells, settlement rods and standpipes.

At the four wick drain swamps within the alignment section between Highway 537 and Gladu Road, the monitoring instruments were installed in early 2007 and embankment construction was carried out between May 2007 and January 2008. Following embankment filling to full height (plus a 2 m high surcharge), the surcharge period continued between January 2008 and June 2009. Throughout the construction, Thurber carried out the monitoring of the field instrumentation.

At the two wick drain swamps within the alignment section from south of Estaire to Highway 537, the monitoring instruments were installed in May and June 2007 and embankment construction was carried out between June 2007 and October 2007. Following embankment filling to full height (plus a 2 m high surcharge), the surcharge period continued between October 2007 and June 2009. Throughout the construction, Golder carried out the monitoring of the field instrumentation.

A number of factors affected the quality of the monitoring data collected at the sites, including the actual rate of construction being slower than assumed in the design analysis in some areas as well as damage to some instruments that were not replaced. As a result, of the six (6) wick drain swamps noted above, only four (4) of the swamps provided sufficiently useful monitoring data to attempt to back calculate parameters (i.e. smear ratio) critical to the design. These swamps are designated as:

- Swamp 'D' and Swamp 'B'
  (Golder designed and Thurber monitored)
- Swamp '605' and Swamp '602'
  (Thurber designed and Golder monitored)

Of these four swamps, the two with the best monitoring data are designated as Swamp 'D' (from the Golder designed section) and Swamp '605' (from the Thurber designed section). A brief summary of the salient geotechnical parameters for Swamp 'D' and Swamp '605' are provided in Tables 4 and 5, respectively. A full description of the subsurface conditions at all of the swamp crossings is provided in Golder (2005), Peto (2004) and Thurber (2006).

Table 4. Swamp 'D' – Parameters for Clayey Strata

Parameter	Value
Thickness of Clay Stratum	10 m to 22 m
Undrained Shear Strength, s_u	>50 kPa (crust)
	25 to 50 kPa (below crust)
Effective Friction Angle, ϕ'	26^o to 28^o
Over-Consolidation Ratio, OCR	>3 (crust)
	3 to 1 (below crust)
Void Ratio, e_o	0.9 to 1.30
Compression Index, C_c	0.3 to 0.8
Recompression Index, C_r	0.04 to 0.1
Water Content, w_n	19% to 72%
Plastic Limit, w_P	13% to 26%
Liquid Limit, w_L	27% to 69%
Liquidity Index	0.6 to 1.8 (1.1 avg.)
Sensitivity, S_t ($s_{u(und)}/s_{u(rem)}$)	3 to 6 (4 avg.)
Coefficient of Consolidation (c_h)	3.5 x 10^{-3} cm^2/s
Ratio of c_h/c_v	1.8
Coefficient of Compressibility (m_v)	2.2 x 10^{-4} kPa^{-1}
Wick Drain Installation Pattern	Triangular
Drain Spacing	1.5 m

Table 5. Swamp '605' – Parameters for Clayey Strata

Parameter	Value
Thickness of Clay Stratum	2.5 m to 10 m
Undrained Shear Strength, s_u	≥ 50 kPa (crust)
	20 to 45 kPa (below crust)
Effective Friction Angle, ϕ'	N/A
Over-Consolidation Ratio, OCR	5 to 2 (crust)
	1.1 to 1 (below crust)
Void Ratio, e_o	0.80 to 1.47
Compression Index, C_c	0.2 to 0.7 (est.)
Recompression Index, C_r	0.01 to 0.1 (est.)
Water Content, w_n	22% to 60%
Plastic Limit, w_P	16% to 23%
Liquid Limit, w_L	23% to 53%
Liquidity Index	N/A
Sensitivity, S_t ($s_{u(und)}/s_{u(rem)}$)	2 to 4
Coefficient of Consolidation (c_h)	3.1 to 8.8 x 10^{-3} cm^2/s
Ratio of c_h/c_v	2.5
Coefficient of Compressibility (m_v)	N/A
Wick Drain Installation Pattern	Triangular
Drain Spacing	1.8 m

6 BACK ANALYSIS OF SMEAR RATIO

To obtain a better understanding of the appropriate value(s) of the smear ratio (k_h/k_s) to be used for the design of wick drain foundation systems in Northern Ontario, a back analysis and matching exercise was carried out using the results of the pore pressure measurements in the vibrating wire piezometers (VWPs) collected as part of the foundation monitoring during the embankment construction and surcharging in Swamps 'D', 'B', '605' and '602'.

In the analyses, the same key geotechnical parameters assessed and used as part of the original wick drain design to estimate the rate of consolidation were maintained (i.e. coefficient of horizontal consolidation, c_h, ratio of c_h/c_v, coefficient of compressibility, m_v), only the smear ratio was varied to provide comparison with the field measured data. In all of the analyses, an average value of d_s/d_m ratio of 3.5 was assumed. In addition, the actual dimensions of the wick drain(s), the size of the mandrel used for the installation at the sites, and the wick drain discharge capacity as specified by the manufacturer were utilized, as follows:

- Wick Drain Dimensions = 100 mm x 3.6 mm
- Mandrel Dimensions = 125 mm x 50 mm
- Discharge Capacity of Wick Drain = 3150 m^3/year

Not all of the results can be included here, however the back analysis and matching for six (6) VWPs in Swamp 'D' is shown on Figure 3. Similarly, the results of the analysis and matching for four (4) VWPs in Swamp '605' are shown on Figure 4. The difference in the amount of the field monitoring data shown in Figure 3 and 4 is due to the method in which the data was collected. For Swamp 'D' (Figure 3), the VWP data was collected manually by periodic visits to the site at key points in the construction. For Swamp '605' (Figure 4), the VWP data was collected and stored in a data logger on site at 6 hour intervals.

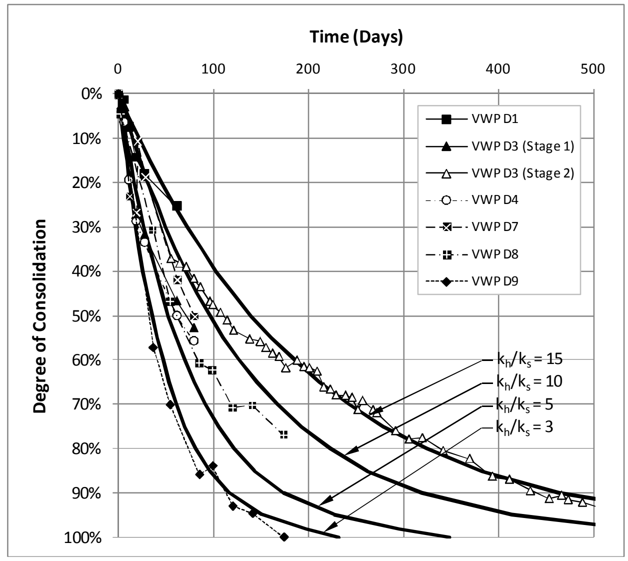

Figure 3. Results of Back Analysis for Six VWPs in Swamp 'D'

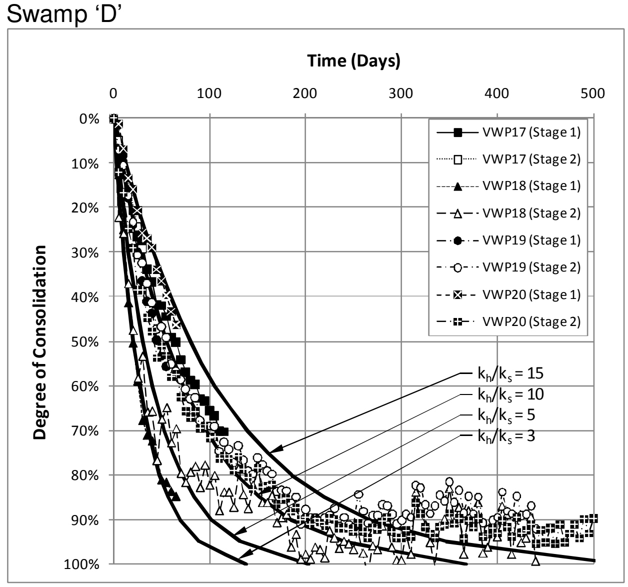

Figure 4. Results of Back Analysis for Four VWPs in Swamp '605'

Table 6 summarizes the values of smear ratio back calculated from all of the analyses for Swamps 'D', 'B', '605' and '602'. Estimated values of k_h/k_s are presented for both the 'early-time' (U<70%) and 'end-time' (U>70%) of the field measured data. This difference in the data matching is shown on Figure 5 for VWP16 in Swamp '605'.

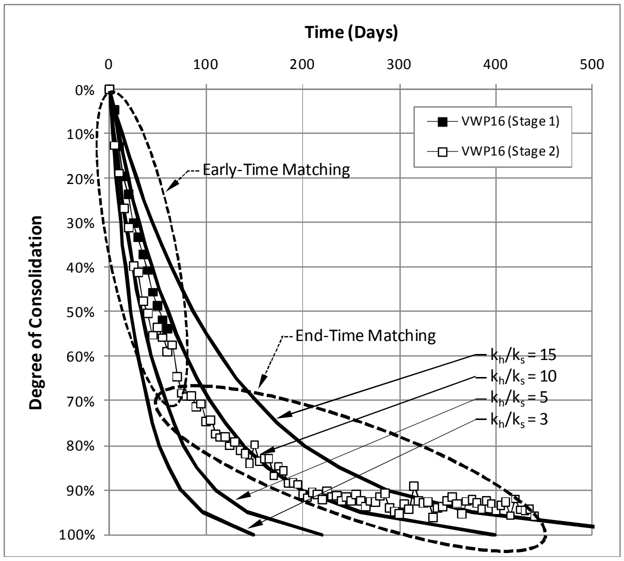

Figure 5. Comparison of early-time and end-time Matching for VWP16 in Swamp '605'

In some cases, for example as shown on Figure 5, the theoretical rate of pore pressure dissipation/degree of consolidation (regardless of the value of k_h/k_s) does not match the field measured response of the VWPs for the entire data range. A discussion of this phenomenon and the interpretation of the results is presented in Section 7.

Table 6. Results of Back Analysis for Smear Ratio.

Swamp 'D'		
VWP	k_h/k_s (early-time)	k_h/k_s (end-time)
D1	10	15
D3 (Stage 1)	4	7
D3 (Stage 2)	9	15
D4	3	5
D7	5	7
D8	6	6
D9	3	3
Swamp 'B'		
VWP	k_h/k_s (early-time)	k_h/k_s (end-time)
B5	5	15
B6	5	15
B8	5	10
B12	5	10
Swamp '605'		
VWP	k_h/k_s (early-time)	k_h/k_s (end-time)
11 (Stage 1)	4	5
11 (Stage 2)	4	5
13 (Stage 1)	3	3
13 (Stage 2)	4	5
14 (Stage 1)	5	5
14 (Stage 2)	5	7
15 (Stage 1)	N/A	N/A
15 (Stage 2)	5	7
16 (Stage 1)	9	9
16 (Stage 2)	5	10
17 (Stage 1)	10	10
17 (Stage 2)	11	11
18 (Stage 1)	3	3
18 (Stage 2)	3	7
19 (Stage 1)	8	8
19 (Stage 2)	10	12
20 (Stage 1)	15	15
20 (Stage 2)	7	10
Swamp '602'		
VWP	k_h/k_s (early-time)	k_h/k_s (end-time)
4	3	5
Summary		
Minimum =	3	3
Maximum =	15	15
Mean =	6	8.5
Mode =	5	5

7 DISCUSSION OF RESULTS

Based on the estimated values of smear ratio for the various VWPs in the swamps as tabulated above, the smear ratio (k_h/k_s) ranges from a low of 3 to a high of 15, with an average or mean value of about 6 and a mode value of 5, for the early-time portions of the data (i.e. for approximately U<70%). A histogram showing the distribution of the back calculated smear ratio values (for early-time matching) is shown on Figure 6.

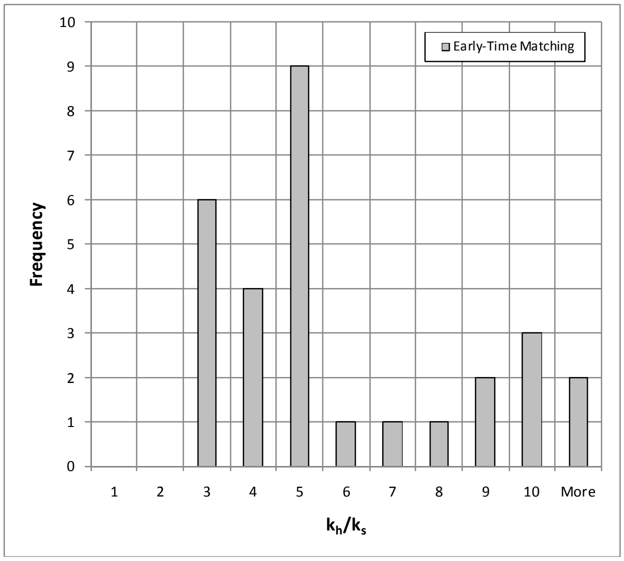

Figure 6. Histogram showing Distribution Frequency of k_h/k_s for 'Early-Time' Matching.

Although the plot presented on Figure 6 shows that about 70% of the back calculated smear ratio values range from 3 to 5 for the early-time data, with a value of k_h/k_s = 5 occurring most frequently (mode value), it is interesting to note the range and distribution of the other values. The large overall range of values may be a result of any one of numerous factors as outlined below.

Lower Values of k_h/k_s Possibly Due To:

- Natural variation in soil (i.e. zones or layers within the clay stratum with higher permeability and/or higher coefficient of consolidation).
- Heterogeneous strata (i.e. localized sand or silt seams and layers which could provide a shorter natural drainage path).
- Out-of-plumb installation of wick drains and/or VWP tips resulting in shorter drainage path than assumed in theoretical analysis.

Higher Values of k_h/k_s Possibly Due To:

- Natural variation in soil (i.e. zones or layers within the clay stratum with lower permeability and/or lower coefficient of consolidation).
- A decrease in the permeability of the soil during the consolidation process (i.e. k_h and c_h are likely not constant values and in reality are a function of the void ratio of the soil at any given time which is decreasing during consolidation).

It is noted that the theoretical decrease in the permeability of the soil during consolidation (as noted in the last bullet above) is the most likely explanation of why
(in some cases) the value of k_h/k_s varies from the 'early-time' data to the 'end-time' data in Table 6.

8 ESTIMATING SMEAR RATIO A PRIORI

Given the importance of the value of the smear ratio (k_h/k_s) parameter in wick drain design and its effect on estimating the rate of consolidation, it is surprising that there has been little research carried out to develop an empirical approach to estimating its value for design. Most design engineers may opt to select a value of k_h/k_s = 3 based on review of some of the suggestions in literature. However, as described in Section 3, a variation in the actual value of the smear ratio (i.e. from 3 to 5) will result in an about 50% increase in the estimated time to reach t_{90}.

It is often noted in literature that where the size and scope of a project permits, the best method of evaluating the smear ratio is to construct a well instrumented test embankment and trial wick drain system and based on the monitoring data, carry out back analysis to evaluate the unknown parameter. This information will then be used to refine the design for the project. In the authors' experience, in practise, this approach is seldom adopted. Instead, design engineers and owners would typically agree to use either a conservative (i.e. high) value or 'typical' (i.e. average) value based on studies reported in literature. Depending on the value selected, this can lead to either a conservative design (with increased costs) or an overly-optimistic design (with potential delays, construction claims and increased costs). Considering the potential impacts of a design based on an erroneous value, some guidance is required for the design engineer.

Since the process of pushing the installation mandrel into the ground results in a localized remoulding of the soil within a zone around the drain, it has been suggested (FHWA, 1986) that some measure of the soils sensitivity may provide a measure of the susceptibility to installation disturbance. Given this, it is hypothesized that a soil's Sensitivity (S_t) or Liquid Limit (w_L) could form the basis of an empirical correlation to the value of the smear ratio. The following sections attempt to investigate these potential relationships as a starting point for future research.

8.1 Sensitivity (S_t)

The sensitivity ($S_t = s_{u(und)}/s_{u(rem)}$) of the soils in Swamps 'D', 'B', '605' and '602' based on in situ field vane shear testing ranges from about 2 to 5 with a average value of 3.5 and a standard deviation of about 1.5. Assuming an average value of S_t = 3.5 for the clayey soils investigated here and a back calculated value of smear ratio of about 5 (early-time) as described previously, the following simple relationship is proposed for consideration:

$k_h/k_s \approx 1.5\ S_t$ [1]

More research involving back analysis from additional case studies is required to support this hypothesis, however, the correlation proposed in Equation [1] could be a starting point in cases when no other information is available.

8.2 Liquid Limit (w_L)

The well known empirical correlation in NAVFAC DM-7, (U.S. Navy, 1971) relating c_v for normally consolidated and remoulded soils to Liquid Limit (w_L) also provides the basis of a possible correlation to estimate the smear ratio.

The Liquid Limit of the soils in Swamps 'D', 'B', '605' and '602' based on laboratory testing ranges from about 21% to 69% with a median value of 43% and a standard deviation of about 12%. For an average value of w_L = 43% for the clayey soils investigated here, the correlation by U.S. Navy (1971) would indicate the following:

- $c_{v(\text{normally consolidated})} = 2.5 \times 10^{-3}\ cm^2/s$
- $c_{v(\text{remoulded})} = 6.5 \times 10^{-4}\ cm^2/s$
- $c_{v(n/c)}/c_{v(rem)} \approx 4$

Given this and assuming a back calculated value of smear ratio of about 5 (early-time) as described previously, the following simple relationship is proposed for consideration:

$k_h/k_s \approx 1.5\ c_{v(n/c)}/c_{v(rem)}$ [2]

Similar to Equation [1], more research involving back analysis from additional case studies is required to support this hypothesis, however, the correlation proposed in Equation [2] could also be a starting point in cases when no other information is available.

9 SUMMARY AND CONCLUSIONS

Based on the results of the back analysis and comparison with field monitoring VWP data from four (4) swamp areas with embankments on wick drain foundations, it appears that the smear ratio (k_h/k_s) for wick drain design may range from as low as 3 to as high as 15, even for one geographic area. However, a value of about 5 appears to be most representative, at least for the 'early-time' portion (i.e. for approximately U<70%) of the consolidation/pore pressure dissipation, for clayey soils in Northern Ontario. It should be understood, however, that when a design is based on a single, most likely value of smear ratio, local variations may result in some portions consolidating at a slower rate than the overall average.

The estimated rate of consolidation is sensitive to the value of smear ratio assumed in wick drain design. While a smear ratio of 3 is often considered as a reasonable average value, at the sites investigated herein, where it appears a smear ratio of 5 is more appropriate, consolidation could take approximately 50% longer than a design based on a value of 3.

Even higher values of smear ratio may be applicable in some cases or areas. For example, for the sites examined, the data from the back analysis suggests that the 'end-time' portion of the dissipation (i.e. for approximately U>70%), is better represented by a value of smear ratio closer to 8.5. This observation indicates that, in reality, the smear ratio is not necessarily a single or constant value and likely decreases with void ratio during consolidation. This finding suggests that for the final stage of embankment construction, the final preload or surcharge period could take longer than the time predicted based on a single value of smear ratio.

A working hypothesis that proposes two potential empirical correlations for guidance in estimating the smear ratio (k_h/k_s) during design has been suggested. Additional research and comparisons of data from other wick drain sites will be needed to support, refine or refute these proposals. In this regard, it is clear from the data plots presented herein that the use of a data logger to collect pore pressure data from VWPs during field monitoring has many benefits over the traditional method of taking manual period readings, especially when using the data for back analyses.

Finally, although in reality the smear ratio may be variable, and the range of actual values may be large even for one geographic area (i.e. varying from 3 to 15 for the sites investigated), in the authors' opinion, utilizing the most conservative value and/or attempting to modify the value of k_h/k_s as a function of stress level or degree of consolation is unwarranted in most design cases. An average value should be assumed for design simplicity. The potentially higher values of k_h/k_s at some locations and/or its change/increase as a result of consolidation will likely be partially off-set by the presence of more permeable zones in the clayey soil and by the actual rate of embankment construction being slower than assumed in the theoretical design. These factors will most likely partially compensate for any lack of conservatism in the selection of the smear ratio in design.

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