A Review of Prediction Methods of Primary Consolidation Settlement from Field Monitoring Data During Highway Embankment Construction: Three Case Studies

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ABSTRACT
The assessment of the degree of consolidation (U) from monitoring data collected during embankment construction has engineering and contractual implications. Estimating U during construction can be critical to confirm that adequate shear strength gain has occurred during hold periods between lift placements to avoid embankment instabilities, and/or that sufficient settlement has been achieved prior to the end of a preload/surcharge period to maintain conformance with post-construction settlement tolerances. Various methods have been suggested by researchers to estimate the degree of primary consolidation achieved during construction, with two commonly implemented approaches being: a comparison of peak pore water pressure measurements to the measurements at the time of the assessment, and an observational method utilizing available settlement data (Asaoka, 1978). For both approaches, uncertainty exists as to the accuracy of the prediction of degree of consolidation; therefore, it is often necessary to supplement the predictions with engineering judgement when making decisions that could affect construction costs and schedule. Three Ministry of Transportation, Ontario (MTO) highway embankment sites in Northern Ontario are examined where foundation monitoring data was collected throughout embankment construction, the preload or surcharge period has been completed, and the end of primary consolidation settlement has been achieved. The range of error in estimating the degree of primary consolidation at various points in time during construction are explored utilizing pore water pressure data, settlement data in conjunction with the Asaoka method, as well as ‘curve-fitting’ to attempt to match model predictions to monitoring data. Best practices for reducing the uncertainty of the predictions are presented.

RÉSUMÉ
L'évaluation du degré de consolidation (U) lors de la construction des talus a des implications techniques et contractuelles. La détermination de U peut être essentielle pour confirmer qu'un gain de résistance au cisaillement adéquat s'est produit pendant les périodes d’arrêts entre les rehaussements pour éviter les instabilités du talus, ou qu'un tassement suffisant a été obtenu avant la fin d'une période de précharge / surcharge pour maintenir la conformité avec les tolérances de tassement requises après la fin des travaux de construction. Diverses méthodes ont été suggérées par les chercheurs pour estimer le degré de consolidation primaire obtenu lors des travaux de construction, avec deux approches couramment utilisées : l’une compare des mesures de pression interstitielle de pointe avec les mesures au moment de l'évaluation, et l’autre utilise des observations de données de tassement disponibles (Asaoka, 1978). Pour les deux approches, une incertitude existe pendant la construction quant à l'exactitude de la prédiction du degré de consolidation. Par conséquent, il est souvent nécessaire lors de la prise de décision d’ajuster ces prévisions par un jugement technique qui est susceptible d'influer les coûts et le calendrier des travaux. Trois sites de travaux routiers du ministère des transports de l'Ontario (MTO) dans le Nord de l'Ontario sont examinés où les données de surveillance des fondations des talus ont été recueillies tout au long de la construction. Pour ces sites, la période de précharge ou de surcharge est terminée lorsque la fin de la consolidation primaire est atteinte. La marge d'erreur dans l'estimation du degré de consolidation primaire à divers moments pendant la construction est explorée en utilisant les données de pression interstitielle et les données de tassement conjointement avec la méthode Asaoka, ainsi que l'ajustement de la courbe pour tenter de faire correspondre les prévisions du modèle aux données de surveillance lors des travaux. Les meilleures pratiques pour réduire l'incertitude des prévisions sont présentées.

1 INTRODUCTION

For embankment construction, interpretation of field monitoring data is required throughout construction to confirm that embankments are safely built to avoid instabilities and to check that acceptable post-construction embankment performance will be achieved. Engineering judgement in combination with data interpretation methods are required during construction with respect to the degree of consolidation to assess whether adequate strength gain and settlement have occurred prior to proceeding with the subsequent stage of construction. The decisions made during construction must also consider schedule and cost implications. Therefore, as both post-construction settlement and strength gain are dependent on the degree of primary consolidation (U), an accurate assessment of U is essential to decide whether construction is proceeding in accordance with design and to allow relevant stakeholders to make informed decisions, when required.

Methods of assessing U often include measuring excess pore pressure build-up and dissipation using instrumentation such as vibrating wire piezometers (VWPs), or evaluating settlement data obtained from instrumentation such as surveyed settlement plates (SPs) or shape accelerometer arrays (SAAs). Making decisions during construction is often difficult considering that only a portion of the monitoring data is available at the time of assessment and the reliability of the interpretive methods is relatively unknown.

This paper focuses on three case studies in Northern Ontario where long-term settlement and pore pressure monitoring was carried out past the end of primary (EOP) consolidation. Three common methods have been used to estimate the degree of consolidation (U) and the predicted total magnitude of primary consolidation settlement at different points in the construction, which are then compared with the actual values determined at the end of the preload/surcharge period. For the purposes of the discussion herein, only primary consolidation during construction is considered; methods for estimating secondary compression have not been evaluated.

2 PROJECT DESCRIPTIONS

2.1 Swamp D – Highway 69, City of Greater Sudbury

King's Highway 69 is a major transportation route in Ontario, connecting the City of Barrie in Southern Ontario to the City of Greater Sudbury in Northern Ontario. As part of highway improvements along this corridor, portions of the highway have been increased from two lanes to four lanes to accommodate increased traffic volumes. The Swamp D crossing is located near the southernmost limits of the City of Greater Sudbury, Ontario, and consists of an approximately 500 m long swamp area with bedrock outcrops exposed on either side of the swamp. To accommodate four-laning through Swamp D, construction of an up to 10 m high, more than 70 m wide embankment was required through the relatively flat and low-lying swampland. A photograph of the Swamp D site is presented on Figure 1.

Figure 1. Photograph of the Swamp D southbound lane embankment, facing south from north limits

The boreholes in the deepest part of the swamp encountered a thin organic layer underlain by up to about 23 m of varved/laminated soft to stiff clayey silt to clay, which was subsequently underlain by more than 10 m of silt to sandy silt.

The predicted total settlement of the foundation was approximately 1600 mm. Wick drains installed at 1.5 m triangular spacing designed to fully penetrate the clay deposit, staged embankment filling and a 2 m granular surcharge were the preferred alternative to maintain stability and to mitigate the post-construction settlements.

Regular monitoring using SPs, VWPs, and Deep Settlement Profilers (DSPs) was carried out during embankment construction and surcharging period and annual readings have been taken following completion of the highway and opening to traffic in 2009. The total embankment settlement measured in the southern portion of the swamp (where the clay stratum was the thickest), was higher than originally estimated such that very little surcharge removal was possible over portions of the alignment.

2.2 Swamp 305 – Highway 69, French River

The Swamp 305 site is located on Highway 69 in French River, Ontario, approximately 56 km south of the Swamp D crossing, and consists of four-laning embankment construction over an approximately 250 m long low-lying swampland with bedrock outcrops visible at the north and south limits of the swamp. A photograph of the Swamp 305 site is presented on Figure 2.

Figure 2. Photograph of the Swamp 305 southbound lane embankment with surcharge in place, facing south from north limits

In general, the boreholes in Swamp 305 encountered surficial deposits of organics, followed by a deposit of sand to silt, underlain by up to about 18 m of very soft to firm clay to clayey silt, underlain by a deposit of loose silt.

The predicted total settlement of the foundation soils was approximately 400 mm. Wick drains installed at 1.5 m triangular spacing, staged embankment filling and a 2 m granular surcharge were the preferred alternative to maintain stability and mitigate the post-construction settlements.

The monitoring program consisted of sixteen VWPs and fourteen SPs installed at arrays along the swamp crossing. Regular monitoring was carried out during construction and surcharge period. The surcharge was removed in February 2019, and the highway is scheduled to be opened to public traffic in 2022.

2.3 Swamp H6/H7 – Highway 66, Virginiatown

King's Highway 66 is a two-lane Trans-Canada Highway in Northern Ontario connecting Ontario and Quebec. A 3.4 km long realignment of Highway 66 from approximately 11.0 km east of the junction of Highway 66 and Highway 624 easterly was constructed due to the risk of surface subsidence associated with the abandoned Kerr-Chesterville underground mine located beneath the footprint of the existing highway alignment. Swamp Crossing H6/H7 consists of an approximately 500 m long swamp area. A photograph of the Swamp Crossing H6/H7 is presented on Figure 3.

Figure 3. Photograph of the Swamp H6/H7 highway realignment, facing east

The boreholes in the swamp encountered up to about 4 m of peat underlain by up to about 17 m of varved clayey silt to silty clay deposit.

The predicted total settlement of the foundation soils were up to 1500 mm. Wick drains installed at 1.5 m triangular grid spacing along with staged construction and surcharging were the preferred alternative to maintain stability and to mitigate the post-construction settlements.

Regular monitoring was carried out during embankment construction and surcharge period with eighteen SPs and twenty-four VWPs. As part of additional research, Swamp Crossing H6/H7 was monitored post-construction with the installation of an additional six VWPs and three Vibrating Wire Inline Extensometers (VWIXs). The highway was opened to traffic in the Fall of 2017.

3 RESULTS OF MONITORING

At Swamp D, DSP readings were taken bi-weekly to monthly during fill placement and hold periods, and about monthly after the surcharge placement. VWP Readings (VWPD1 and VWPD3) were collected from daily to monthly intervals during fill placement, and about weekly to monthly after surcharge placement. The monitoring instrument readings at the location corresponding to the most settlement are presented on Figure 4.

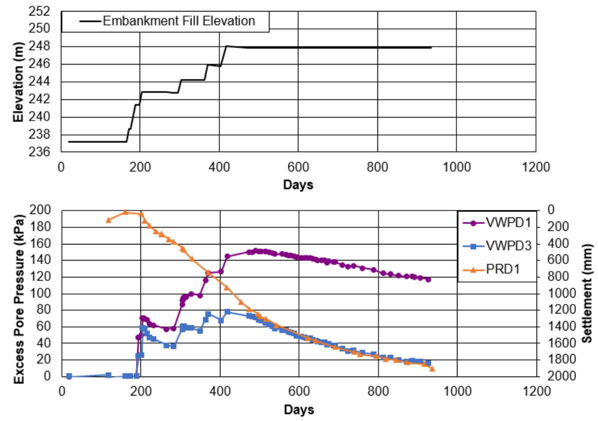

Figure 4. Settlement profiler and vibrating wire piezometer data at Swamp D

At Swamp 305, SP readings were taken bi-weekly to monthly during the surcharge hold period. VWP28 collected data twice daily (at 12:00AM and 12:00PM). The monitoring instrument readings corresponding to the highest magnitude of settlement at Swamp 305 are presented on Figure 5.

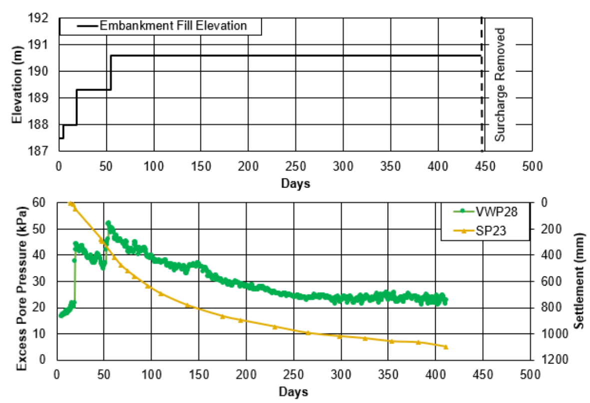

Figure 5. Settlement plate and vibrating wire piezometer data at Swamp 305

At Swamp H6/H7, SP readings were taken daily to monthly during fill placement and hold periods, and daily to about monthly after the surcharge placement. After the installation of the VWIX, a final confirmation reading was taken on SP12, 226 days after the previous measurement from the SP to confirm reliability of the VWIX system. VWP16 collected data twice daily (at 12:00AM and 12:00PM). The monitoring instrument readings for the section of this swamp with the highest magnitude of settlement are presented on Figure 6.

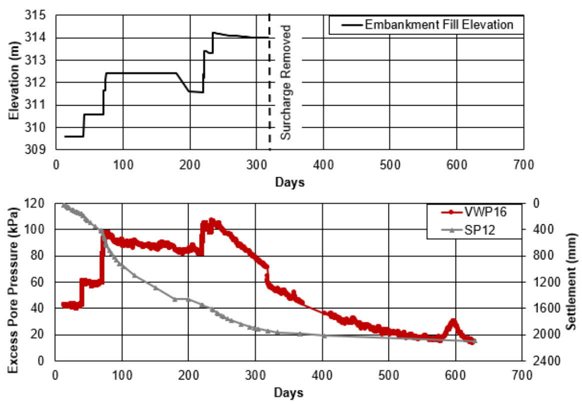

Figure 6. Settlement plate and vibrating wire piezometer data at Swamp Crossing H6/H7

4 DEGREE OF CONSOLIDATION EVALUATION

As some of the methods in this study require monitoring data from within one stage of construction (i.e., under a constant load), in all cases the surcharge period has been examined. In addition, for each method, the analysis was carried out considering monitoring data from 30, 60, 90, 120, 150 and 180 days after completion of surcharge placement, as well as considering all the monitoring data available to observe how the accuracy of the predictions changes over time.

Given the staged nature of the construction at these sites, careful consideration was also required for each prediction method as to whether U should be calculated based on information throughout the multiple stages of construction (i.e., U_{Total}) or whether U should be calculated over solely the surcharge period (i.e., U_{lift}). The following sections outline the assessment methodology used for each prediction method considered.

3.1 The Asaoka Method (1978)

A graphical approach to estimate the end of primary consolidation based on measured field settlement under a sustained load was proposed by Asaoka (1978). A constant time interval, t_n, is selected and the settlement at the time interval, p_n, is plotted against the settlement from the previous time interval, p_{n-1}. A best fit through this data obtains a linear trend, and the end of primary settlement is estimated to be where the trendline intersects a 45-degree line.

As presented in Equation 1, the degree of consolidation is calculated by comparing the settlement at the time of consideration ($\delta_{current}$) with the predicted end of primary consolidation settlement from the Asaoka Method ($\delta_{Asaoka\ EOP}$). The settlement measured up to the time of surcharge placement ($\delta_{surcharge\ placement}$) is removed to consider only the primary consolidation settlement occurring as a result of the surcharge placement.

$$U_{lift} = \frac{(\delta_{current} - \delta_{surcharge\ placement})}{(\delta_{Asaoka\ EOP} - \delta_{surcharge\ placement})} \times 100 \qquad [1]$$

The U_{lift} was selected as the preferred calculation for this method as it discounts settlement that occurred prior to the surcharge period. The calculation of U for the Asaoka prediction could include the settlement prior to surcharge placement (i.e., U_{Total}); however, in consideration of predictive accuracy, the U_{lift} selected discounts settlement that occurred prior to the surcharge period.

A previous study by Arulrajah (2008) using the Asaoka method observed that at a certain point, the time intervals begin to obtain similar results (i.e., a 28-day, 42-day and 56-day interval each estimated similar settlement at end of primary consolidation, δ_{EOP}). Based on the typical survey frequency at the sites under consideration for this study, time intervals of 5, 10, and 30 days were selected for analyses. Another study completed by Mesri and Huvaj-Sarihan (2009) suggested that settlement measured within 40% to up to at least 80% of primary consolidation provides the most reliable estimates when using the Asaoka Method; however, given that during construction the total magnitude of settlement isn't precisely known at the time of assessment, in practice it would be difficult to determine which settlement data to exclude for a more reliable estimate.

3.2 Curve Fitting

A time dependent one-dimensional analysis was carried out using the solution by Hansbo (1979) for consolidation by horizontal drainage within a single vertical (wick drain) drainage cell. The back-analysis was carried out by selecting typical values for the variables representing the wick drain installation disturbance (i.e., d_s/d_m and K_h/K_s) and discharge capacity (q_w) and, while holding these parameters constant, the horizontal coefficient of consolidation (c_h) and final magnitude of settlement at end of primary consolidation (δ_{EOP}) were adjusted until a match was achieved between the predicted settlement versus time and the field measured settlement versus time.

The analyses involved an initial 'back of the envelope' estimate of the magnitude of primary settlement followed by an iterative approach and using engineering judgement to select a curve to fit the trend of the measured field data during the surcharge period. An experienced engineer performed the interpretation without knowledge of the final measured settlement results (i.e., the engineer was only provided the data set that would have been available at the date of assessment during construction). This method also provides an estimate of the in-situ c_h; however, it should be noted that the back-calculated c_h values represent an average value over: (i) the length of the vertical drains/depth of the treated stratum (not individual soil layers within the stratum) and, (ii) the duration of the surcharge period.

For this approach, U_{lift} was preferred based on the same rationale provided for the Asaoka Method and was calculated in a similar manner as Equation 1.

3.3 Excess Pore Pressure

The degree of consolidation can be estimated from the current excess pore pressure ($u_{current}$) and a sum of the measured peak excess pore pressure(s) at the time of fill placement for each lift (u_{peak}) based on the field measurements collected by vibrating wire piezometers. A common approach to interpret the degree of consolidation, referred to as Approach 1 hereafter, is shown in Equation 2.

$$U_{Total} = \left(1 - \frac{u_{current}}{\sum u_{peak}}\right) \times 100 \qquad [2]$$

Note that Equation 2 inherently calculates U_{Total}=100% at the end of primary consolidation when the excess pore water pressure approaches zero; therefore, excess pore water pressure from previous fill placement remaining at the time of surcharge placement must be considered in the calculation of U.

The above noted approach discounts minor fluctuations that occur over small time intervals during construction. Therefore, the degree of consolidation was also assessed considering the cumulative excess pore pressure(s) generated and dissipated over each reading interval (i.e., including the 'fluctuations' during the wait periods). This approach, referred to as Approach 2 herein, is shown in Equation 3.

$$U_{Total} = \left(1 - \frac{\sum \Delta u_{dissipation}}{\sum \Delta u_{generation}}\right) \times 100 \qquad [3]$$

Another uncertainty when considering field porewater pressure data is the potential for displacement (i.e., settlement) of the piezometer tip during consolidation. Given that piezometers are often installed at a depth within a compressible cohesive deposit, the instruments will likely only experience a displacement equivalent to a portion of the overall settlement within the deposit; however, no settlement by depth field data is typically available. Therefore, a third approach to estimate U using excess porewater pressure data was considered; whereby, the results from Approach 2 were further adjusted by assuming the piezometer tips experienced the same displacement as the settlement observed in the cohesive deposit. The authors note that this might be an overestimate of tip displacement, but this is considered a reasonable assumption as no measured settlement data by depth was available. Specifically, in Approach 3, the piezometer tip elevations were corrected for the settlement measured by the nearest settlement plate.

It should also be noted that sub-excavation of the surficial organic deposits at Swamp 305 and Swamp H6/H7 occurred prior to the wick drain and monitoring instrument installation. Therefore, excess pore pressures that developed prior to instrument installation were estimated based on the difference between the assumed unit weights of the organics and granular drainage blanket fill. The validity of this estimate will impact the predicted U_{Total}.

5 RESULTS OF ANALYSIS AND DISCUSSION

In order to allow for a consistent comparison of the results of the various interpretive methods, a single value of the magnitude of EOP settlement was first required. Therefore, the EOP settlement was evaluated for each site by applying both the root-time method (Taylor, 1942) and the log-time method (Casagrande and Fadum, 1940) to the full field monitoring data set(s). The EOP settlement used for comparison purposes was taken as the average of the value obtained from the two methods for Swamp D and Swamp 305. For Swamp H6/H7, the EOP evaluated from only the root-time method was used since limited information in the secondary compression range was available due to the removal of surcharge before much secondary compression had occurred. The authors consider this to be a reasonable approach to obtain an accurate value of the in-situ EOP settlement, and subsequent percent errors presented herein are relative to the calculated values presented in Table 1.

Table 1. End of Primary (EOP) Settlement

Swamp		End of Primary Settlement		
		Root-Time Method	Log-Time Method	Selected for Analysis
D	δ_{EOP} (mm)	2015	2050	2033[1]
	t_{90}[3] (days)	610	N/A	610
305	δ_{EOP} (mm)	1070	1020	1045[1]
	t_{90}[3] (days)	204	N/A	204
H6/H7	δ_{EOP} (mm)	2045	-	2045[2]
	t_{90}[3] (days)	149	N/A	149

[1] average EOP settlement from root-time and log-time methods
[2] EOP settlement from root-time method only
[3] approximate time (in days) for 90% primary consolidation after completion of surcharge placement

Monitoring data collection frequency at the sites varied, which may influence the results. In particular at Swamp D, the first settlement and VWP readings were taken at 30 days and 55 days after completion of surcharge placement, respectively, and therefore U estimates within this time period must consider the limited data. Further, the surcharge at Swamp 305 was removed 79 days after placement; therefore, the assessments beyond this timeframe will be impacted due to the reduced loading conditions.

4.1 The Asaoka Method (1978)

An example of the results of the Asaoka plots (i.e., p_n versus p_{n-1}) for Swamp 305 for the three time intervals considered for this study are presented on Figure 7. Interestingly, increasing the time interval correspondingly increased the slope of the trendline and produced slightly easier to interpret results. A comparison of the percent error for the different time intervals used in the Asaoka analyses for the three swamps is shown in Table 2.

At Swamp D, only limited survey data was available within the 30 day period following surcharge placement making initial predictions not possible. Additionally, the lack of initial data at this site made the interpretation from the data sets at 60 day and 90 days after surcharge placement not feasible (i.e., the trendline did not intersect the 45° line after the data set); hence the large percent error(s).

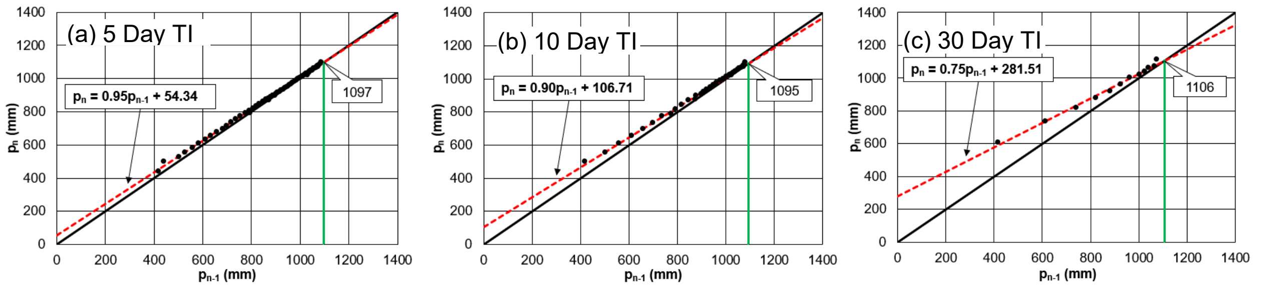

Figure 7. Comparison of Asaoka method analyses used for estimating degree of consolidation from settlement plate survey data at Swamp 305 using (a) 5 day Time Interval, (b) 10 day Time Interval, and; (c) 30 day Time Interval

The large range in percent error observed in the results from Swamp D highlights the importance of obtaining regular, reliable and consistent survey readings throughout the surcharge period, where missed or damaged survey readings can drastically change the accuracy of predictions using the Asaoka method.

Table 2. Comparison of percent error for Asaoka Method with different Time Intervals (TIs) for Swamp D, Swamp 305, Swamp H6/H7

Site	Average Absolute Percent Error (%)		
	5 Day TI	10 day TI	30 day TI
Swamp D DSP1	63	67	533
Swamp 305 SP23	16	21	6
Swamp H6/H7 SP12	13	12	5

It is clear that Swamp D, with the most inconsistent survey readings, provided the largest average percent error regardless of the time interval used to assess the data. In general practice, the early interpretations at Swamp D would likely have been ignored due to the obviously limited data set; therefore, for the purposes of comparison, the Swamp D analyses before 120 days post surcharge placement are not included in the further discussions on the accuracy of this method.

The results from Swamp 305 and Swamp H6/H7 both suggest that the 30 day time interval provided the most accurate estimates, which might be attributed to the fact that the lowest frequency within the survey results also corresponded to about 30 days. Interpretation between the available survey points appears to have reduced the accuracy of the prediction.

The results shown in Table 3 indicate a good agreement between the predicted and measured U_{lift} for the three time intervals at the various time periods (or length of datasets) after surcharge removal. The 30 day Time Interval provided the highest agreement, with one exception for the 120 day dataset attributed to inconsistencies in survey data from Swamp D. The three time intervals generally increase in accuracy with more available data until the EOP is reached. For the larger data sets (i.e., monitoring time frames) beyond EOP, the settlement estimates are impacted by the inclusion of secondary compression.

Table 3. Comparison of percent error for different Time Intervals (TIs) and Datasets (Combined for three sites)

Dataset (Approx. days after Surcharge Placement)	Average Absolute Percent Error (%)[1]		
	5 Day TI	10 Day TI	30 Day TI
30[2]	45	52	N/A
60[2]	16	21	3
90[2,3]	11	14	7
120[3]	12	13	20
150[3]	11	11	7
180[3]	9	9	4
All data[3]	9	9	10

[1] limited data available during the initial 30 days after surcharge
[2] Swamp D interpretations not included before 120 days post surcharge removal
[3] surcharge removed 79 days after placement at Swamp H6/H7

Therefore, based on the three sites considered for this study, with regards to the Asaoka Method, using a 30 day time interval provided the most consistently accurate estimates for degree of consolidation regardless of the size of the dataset considered.

4.2 Curve Fitting

An example of the curve fitting and corresponding estimate of settlement at the end of primary consolidation along with the coefficient of horizontal consolidation (c_h) at three different times (datasets) during construction are presented on Figure 8.

Engineering judgement was used to estimate the starting point of primary consolidation from the surcharge placement with respect to both time (i.e., less than zero) and magnitude (i.e., 100 mm). This was implemented by the engineer based on judgement to compensate for immediate and primary consolidation that may have occurred during the surcharge placement.

The average percent error for the Curve Fitting method is presented in Table 4 for U_{lift}. It can be seen that it varies across the sites, with the lowest accuracy obtained at Swamp 305 at about 33%. At Swamp D, much of the earlier data was observed to be unreliable and was therefore less relied upon by the engineer during the assessment.

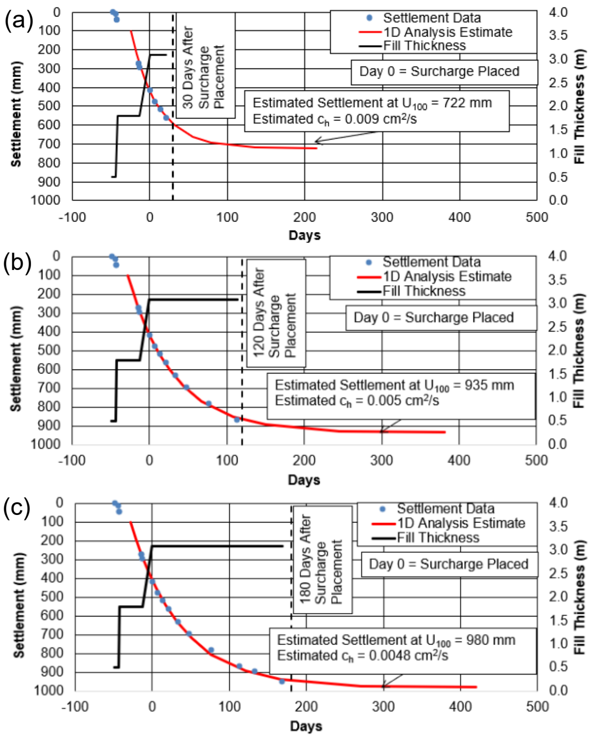

Figure 8. Interpretations from Curve Fitting at Swamp 305 considering: (a) 30 days of data after surcharge placement, (b) 120 days of data after surcharge placement, and; (c) 180 days of data after surcharge placement

Table 4. Comparison of percent error from Curve Fitting method for lower and upper bound estimates for Swamp D, Swamp 305, Swamp H6/H7

Site	Average Absolute Percent Error (%)		
	Lower Bound Estimate	Upper Bound Estimate	Engineer's Selected Estimate
Swamp D	10	10	10
Swamp 305	41	21	33
Swamp H6/H7	3	3	3

Table 5. Comparison of percent error from Curve Fitting method for different Datasets (Combined for three sites)

Dataset (Approx. Days after Surcharge Placement)	Average Absolute Percent Error (%)		
	Lower Bound Estimate	Upper Bound Estimate	Engineer's Selected Estimate
30[1]	106	27	106
60	23	14	17
90[2]	16	14	15
120[2]	12	10	11
150[2]	9	9	9
180[2]	8	8	8
All data[2]	5	5	7

[1]no available information for the first 30 days after surcharge placement at Swamp D
[2]surcharge removed 79 days after placement at Swamp H6/H7

The percent errors summarized in Table 5 indicate that as the available data after surcharge period increases (i.e., the dataset gets larger), the accuracy of the prediction correspondingly increased, with the method achieving a relatively good agreement with the measured U after having about 60 days of data (i.e., within about U= 20%).

4.3 Excess Pore Pressure

An example of the results of the three Approaches considered for estimating the degree of consolidation from the VWP monitoring data are presented on Figure 9.

As shown in Table 6, at each site the average percent error in estimated U based on the EPP method was the largest for Approach 1. On average, the percent error was reduced between 3% and 28% through incorporation of the minor pore water pressure fluctuations as outlined in the methodology for Approach 2, and further improved by between 5% and 11% by adjusting for the piezometer tip settlement as outlined for Approach 3.

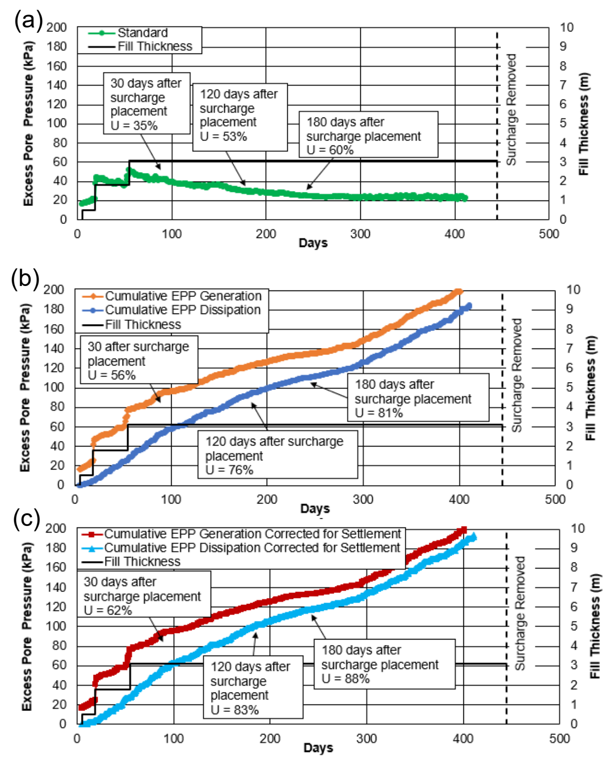

Figure 9. Comparison of approaches for estimating degree of consolidation from excess pore pressure at Swamp 305 using: (a) the standard approach (Approach 1), (b) the cumulative EPP generation and dissipation (Approach 2), and; (c) the cumulative EPP generation/dissipation and adjusting for tip elevation due to settlement (Approach 3)

The U estimated from VWPD1 at Swamp D showed the largest deviations from the actual U measured from the field settlement data. This was expected to show unreliable results given that the excess pore water pressure never returned to pre-construction levels over a year after construction. Although the cause of this inconsistency is unclear to the authors, the results of this VWP were included as each swamp contained VWPs that displayed similar behaviour, highlighting a lack of precision in estimating U when relying exclusively on pore water pressure data. It is possible that some of the variability in the piezometer results may be a result of the varved nature of the clay under consideration.

Table 6. Comparison of percent error for Approaches 1 to 3 for Swamp D, Swamp 305, Swamp H6/H7

Site	Average Absolute Percent Error (%)		
	Approach 1	Approach 2	Approach 3
Swamp D – VWPD1	82	76	69
Swamp D – VWPD3	27	24	13
Swamp 305	38	10	4
Swamp H6/H7	19	10	5

For further assessment considering the accuracy of the EPP Approach with respect to time, VWPD1 results were omitted and a proposed method for assessing which VWPs to exclude during construction will be discussed in the concluding remarks. Table 7 presents the percent error for each of the EPP Approaches based on considering different datasets. For Approach 1, the average percent error decreases (i.e., accuracy increases) over time as additional data becomes available after surcharge placement, up to 150 days. Interestingly, for Approaches 2 and 3, there is no clear trend indicating that the average predicted U becomes more accurate with increased size of dataset. In one instance, at Swamp H6/H7, Approach 2 was the most accurate approach past 150 days; however, this is likely attributed to surcharge removal before the end of the timeframe under consideration.

Table 7. Comparison of percent error from EPP Method for Approaches 1 to 3 for different Datasets (Combined for three sites)

Dataset (Approx. Days after Surcharge Placement)	Average Absolute Percent Error (%)[1]		
	Approach 1	Approach 2	Approach 3
30[2]	45	9	7
60	37	19	11
90[3]	30	18	9
120[3]	23	15	7
150[3]	21	14	5
180[3]	22	13	5
All data[3]	24	9	7

[1]average percent error excluding results from Swamp D VWPD1

[2]no available information for the first 30 days after surcharge placement at Swamp D

[3]surcharge removed 79 days after placement at Swamp H6/H7

It should be noted that the results for the three Approaches rely on the assumed initial pore pressure response due to sub-excavation and drainage blanket placement, as instruments are installed after these construction activities. For example, in the case presented on Figure 9, it appears that the response may have been overestimated. If a lower initial response is utilized, the estimates from Approach 2 and/or 3 would converge closer to the measured U_{Total}.

Based on the three sites considered for this study, with regards to the Excess Pore Pressure Method, Approach 3 (i.e., accounting for small EPP fluctuations and adjusting for VWP tip displacement) provided the most consistently accurate estimates for U_{Total}.

6 COMPARISON OF METHODS

In general, it appears that significant variability exists both between the methods employed to estimate U and with the approach used for each method. In order to allow for an evaluation of the most consistently accurate prediction method, a comparison is made between the preferred approaches from the Asaoka Method (i.e., 30 day TI), and the Excess Pore Pressure Method (i.e., Approach 3), along with the sole approach employed for the Curve Fitting Method; the results are show in Table 8.

Table 8. Comparison of percent error for each method with preferred approach (Combined for three sites)

Dataset (Approx. Days after Surcharge Placement)	Average Absolute Percent Error (%)		
	Asaoka (30 day TI)	Curve Fitting	EPP[2,3] (Approach 3)
30[1]	N/A	106	7
60[1]	3	17	11
90[1,4]	7	15	9
120[4]	20	11	7
150[4]	7	9	5
180[4]	4	8	5
All data[4]	10	7	7

[1]Swamp D interpretations not included before 120 days post surcharge removal

[2]average percent error excluding results from Swamp D VWPD1

[3]no VWP data available for the first 30 days after surcharge placement at Swamp D

[4]surcharge removed 79 days after placement at Swamp H6/H7

Based on the results from the sites considered as part of this study, the Asaoka Method and Excess Pore Pressure Method provided similar accuracy for estimating the degree of consolidation (U). In general, all three preferred methods provided relatively accurate estimates of U and a comparison between the predicted and measured U_{lift} and U_{Total} for each is shown on Figure 10.

In general, the EPP Method indicates a lower degree of primary consolidation during the surcharge period, as compared to that measured; whereas, the Asaoka Method generally indicates higher degree of primary consolidation than that measured. An explanation for this discrepancy could be attributed to the fact that the degree of consolidation estimated from the VWPs is at a single discrete point in the soil deposit; therefore, it is possible that the VWPs under consideration were installed at depths where the degree of consolidation was lower than the average in the deposit.

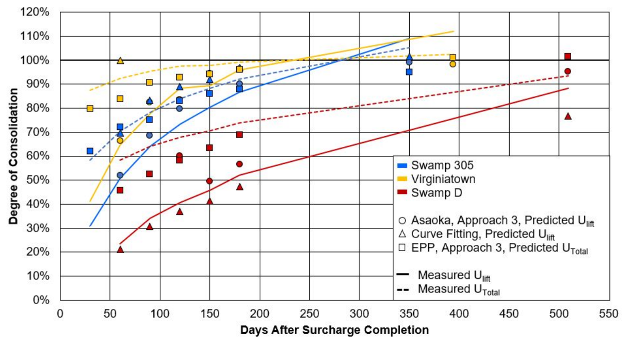

Figure 10. Comparison of predicted degree of consolidation to measured degree of consolidation for three methods

Background water levels can fluctuate and increasing levels (i.e., due to heavy rainfall) will artificially decrease the estimated degree of primary consolidation from EPP. It has been suggested by others that construction of the embankments may permanently alter (i.e., increase) the hydrostatic pore water pressure in the area; however, given the relatively small size of these embankments, in the authors' opinion it would not be likely for these sites. Further, some residual pore pressure remains during secondary compression (Mesri et al., 2005) which, would decrease the estimated degree of primary consolidation. Finally, the varved nature of the clay creates variable excess pore water pressure as the clayey laminae may drain less quickly than the siltier laminae (Milligan et al., 1962).

Lower estimates of the degree of consolidation based on pore pressure data, as compared to settlement data, have been observed by researchers at other sites (i.e., Hansbo, 1979) and in some cases (Hansbo, 1981), in-situ field vane measurements were carried out to assess the magnitude of undrained shear strength (after embankment loading) and strength gain from which the degree of consolidation could be estimated. In these cases, the strength gain from the field vane measurements generally indicated a degree of consolidation that was more consistent with that interpreted from the settlement monitoring data.

Based on the authors' experience at sites involving embankments constructed on soft soils (with and without wick drains), the Asaoka prediction had been considered to generally provide more consistent estimates of U than the pore pressure measurements; however, U estimated from EPP has typically been carried out using Approach 1, which as shown in this paper can be significantly improved by adopting Approach 3. This includes experience at Swamp H6/H7 where field vanes were carried out to evaluate the degree of strength gain/degree of consolidation which showed a better agreement with the Asaoka prediction than with that estimated from the pore pressure data using Approach 1.

The analyses carried out by the Curve Fitting Method to the field settlement data did not result in better accuracy than the Asaoka or EPP Methods (especially at early times/small datasets) even with the interpretations carried out using the judgement of an experienced engineer. However, the Curve Fitting Method was observed to be better than the Asaoka Method at Swamp D, where some erroneous survey measurements were noted in the dataset. The accuracy of the Curve Fitting method will largely depend on the past experience of the engineer carrying out the settlement analysis with wick drains.

In practice, each method has its own benefits and limitations that need to be considered when developing a monitoring program and when interpreting the degree of consolidation from the available monitoring data during construction.

The Asaoka Method relies heavily on accurate survey readings taken at a regular frequency and in a consistent manner. Settlement plates are the most commonly utilized instrumentation for monitoring settlements and require that the settlement rods extend through the fill and to the top of the embankment platform during construction. Each rod extension, if not carefully measured before and after placement, will introduce survey error which will impact the resulting estimates of U. Further, due to constructability requirements and the location of the instruments, heavy equipment often operates in close proximity to the instruments. In the authors' experience, the settlement rods are the most frequently damaged instruments and most likely to have erroneous measurements; therefore, redundancy in the monitoring program and site observations are essential with this method.

The Curve Fitting Method is similarly impacted by the survey measurements and relies heavily on the experience of the engineer completing the assessment. Although overall the accuracy was slightly lower with this method, as seen in Swamp D engineering judgment can greatly improve the accuracy in locations having less reliable data. In addition, this method provides back calculated estimates of c_h, which can be critical for validation of subsequent hold periods specified based on the design.

The Excess Pore Pressure Method for estimating U is very sensitive to the method utilized for interpretation as well as the selected VWP data. It is recommended that Approach 3 presented herein be utilized, with due consideration given to the possible pore pressure generation from construction activities prior to instrument installation (i.e., sub-excavation and drainage blanket placement) and the magnitude of settlement occurring below the VWP tip elevation (i.e., settlement calculation estimates may be required) as these two factors will significantly impact the accuracy of the method. Although the reason is not known, in the authors' experience, the EPP measured at some VWPs does not fully dissipate, creating an unreliable interpretation of U if an assessment is carried out on these particular instruments.

Therefore, it is recommended that the results from the Asaoka and Curve Fitting Methods firstly be used to provide an estimate of U and total final settlement, from which VWPs can be selected for assessment that are most representative of where the settlement is occurring at the site. In this manner, the interpretations will provide more reliable results and the VWPs can contribute to the redundancy in the monitoring program in the event the settlement plates are damaged and/or erroneous survey readings occur. In short, all three Methods should be utilized.

7 CONCLUSIONS

The monitoring results from three embankment construction sites involving wick drains and thick clay deposits have been examined to evaluate the accuracy of three different methods for estimating the degree of consolidation (U) during construction.

From a construction perspective, the evaluation of the degree of consolidation requires a clear understanding of the benefits and limitations of the different predictive methods. Time sensitive decisions are required during construction to avoid contractual delays and additional mitigative strategies. These decisions are based on the interpretations of the data from the settlement and pore pressure monitoring instruments which are used to assess: (i) the current degree of consolidation, (ii) the rate of consolidation, and (iii) the total final settlement which is then compared to the design predictions. In order to minimize the risk of poor post-construction roadway performance, and ultimately additional maintenance, logical and reliable method(s) of data interpretation are required, which is the rationale for the detailed study presented in this paper.

Following a comparison of predictions of the degree of consolidation from the Asaoka Method, the Curve Fitting Method, and the Excess Pore Pressure Method to the actual values measured based on the data at the end of construction, the following observations were noted:

i) On average, the percent error from the preferred approaches of the Asaoka Method and the Excess Pore Pressure Method produced estimates of degree of consolidation that were generally within about 10% of the measured values. The Curve Fitting Method produced estimates that were generally within about 20% of the measured values, with significant improvement in accuracy as days increased from surcharge placement.

ii) For the Asaoka Method, using an approach with a standard time interval of 30 days produced the least amount of error (i.e., was the preferred) as compared to 5 day and 10 day time intervals. The Asaoka Method relies heavily on the frequency and quality of the survey data. Given that survey rods are typically located in areas of heavy construction traffic; redundancy in the monitoring program (i.e., in the number of SPs) is critical.

iii) For the Curve Fitting Method, in addition to the survey measurements, the accuracy of the estimate of U relies on the experience of the engineer completing the assessment. Although, on average, producing slightly less accurate results in this study, the Curve Fitting Method performed better than the Asaoka Method where unreliable survey data was present, likely due to the judgement of the engineer to ignore select (erroneous) data points.

iv) For the Excess Pore Pressure Method, the incorporation of small cumulative EPP fluctuations between readings significantly improved the accuracy of the estimated degree of consolidation. Further refinement was achieved by adjusting the data for displacement of the VWP tip elevation using a conservative assumption of settlement (i.e., Approach 3). Selection of the VWP is critical to this method as, in the authors' experience, measured EPP at some VWPs do not fully dissipate.

Overall, the methods for evaluating the degree of consolidation (U) during construction considered herein provided relatively good agreement with the measured U. The Asaoka Method tends to slightly overestimate the degree of consolidation; whereas, the EPP Method tends to slightly underestimate the degree of consolidation. The three methods each have benefits and limitations and therefore, depending on the site conditions, the most appropriate method to use could vary. Therefore, it is recommended that in practice engineers implement the following approach:

i) Evaluate U_{lift} from various settlement plates using the Asaoka Method with a 30 day time interval.

ii) Complete a second estimate of U_{lift} from the same data set using the Curve Fitting Method.

iii) Carry out U_{Total} estimates, adjusting for minor cumulative EPP fluctuations during wait periods and settlement of the VWP tip, from available VWP data at locations in proximity to the settlement plates under consideration. The VWPs that produce an estimate of U slightly below that from the Asaoka Method (or Curve Fitting Method if erroneous data is encountered) are likely to provide the most accurate estimate of in-situ U for the site.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Ministry of Transportation, Ontario (MTO) for making the monitoring data from the three sites available for use in this study.

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