Rock Fill Settlement in a Highway Embankment in Northern Ontario: A Case Study (Final Results)

A.K. De Souza[1], A. Bom[1], J. P. Dittrich[2], T. Sangiuliano[3], and K. Ahmad[3]
1. Golder Associates Ltd., Sudbury, Ontario, Canada
2. Golder Associates Ltd., Mississauga, Ontario, Canada
3. *Ministry of Transportation, Ontario - Foundations Section, Toronto, Ontario, Canada*

ABSTRACT
Rock fill embankments are susceptible to immediate, short-term, and long-term settlements. This paper presents the final results of a four-year study carried out at a 20 m high rock fill embankment in Ojibway Canyon along Highway 69, near French River in Northern Ontario. Three different methods of rock fill placement/compaction were employed at three sections of the embankments, including: 1) placement/compaction method in accordance with Ontario Provincial Standard Specification (OPSS.PROV 206); 2) placement/compaction method in accordance with OPSS.PROV 206 but compacted by a vibratory drum roller; and, 3) rock fill sizes in accordance with OPSS.PROV 206 but with no maximum lift thickness and no specified compactive effort. A comprehensive settlement monitoring program was implemented to measure immediate, short- and long-term settlements. The settlement instrumentation includes: (i) settlement plates installed at different depths/heights within the embankment to measure the magnitude of fill settlements (as well as foundation soil settlements); and, (ii) shape accelerometer arrays (SAAs) to provide a settlement-deflection profile across the entire cross-section of the embankment(s). Measurements have been taken at specified intervals of time to evaluate the immediate, short- and long-term settlement behaviour of the rock fill embankment(s). The purpose of the settlement monitoring is to validate a MTO Guideline (September 2010) for estimating short- and long-term settlements within rock fill embankments and to study the effect of different placement/compaction methods on rock fill settlement. This paper is a summary of the study, following-up on two previous interim papers (Varshoi, et al. 2017; and Bom, et al. 2019) presenting the final long-term monitoring results and conclusions. The paper presents and interprets the short-term (immediately after construction) and final long-term (creep), post-construction monitoring data collected between June 2017 and April 2021, and provides a comparison to the method(s) in the MTO Guideline (September 2010) for estimating rock fill settlements.

RÉSUMÉ
Les remblais rocheux sont sujets à tassements immédiats, court terme et long terme. Ce document présente les résultats finaux d'un programme de surveillance de tassement de quatre ans réalisé d'un remblai rocheux d'une hauteur de 20 m dans le canyon Ojibway sur la nouvelle autoroute 69, près de la rivière des Français dans le nord de l'Ontario. Trois méthodes différentes de mise en place/compactage du remblai ont été employées sur trois sections, y compris 1) méthode de mise en place/compactage conformément à la spécification provinciale de l'Ontario (OPSS.PROV 206), 2) méthode de mise en place/compactage conformément à OPSS.PROV 206 mais compacté par un rouleau à tambour vibrant, et 3) des tailles de remblai rocheux conformes à OPSS.PROV 206 mais sans épaisseur de levage maximale et sans effort de compactage spécifié. Un programme de surveillance a été mis en œuvre pour mesurer les tassement immédiats, à court terme et à long terme. L'instrumentation de tassement comprend: (i) des plaques de tassement installées à différentes profondeurs à l'intérieur du remblai pour mesurer l'ampleur des changements de tassement (et au sol de fondation); et (ii) matrice d'accéléromètres pour fournir un profil de tassement-déviation sur toute la section transversale du remblai rocheux. Des mesures ont été prises à des intervalles de temps spécifiés pour évaluer le comportement de tassement, immédiatement, à court et à long terme des remblais rocheux. Le but de la surveillance du tassement est de valider une ligne directrice du MTO (septembre 2010) pour estimer les tassements à court et à long terme dans les remblais rocheux et d'étudier l'effet de différentes méthodes de placement/compactage sur le tassement du remblai rocheux. Ce document est une sommaire de cette étude et fait suite aux documents intérimaires précédents (Varshoi, et al. 2017; and Bom, et al. 2019), et présente les résultats long terme et conclusions. Le document présente et interprète les données de surveillance post-construction à court terme (immédiatement après la construction) et finales à long terme recueillies entre juin 2017 et avril 2021, et fournit une comparaison des methodes dans la ligne directrices du MTO (septembre 2010) pour l'estimation des tassements d'enrochements.

1 INTRODUCTION

Rock fill is frequently used to build highway embankments for Ministry of Transportation, Ontario (MTO) projects in Northern Ontario. Rock fill embankments can experience relatively large settlements depending on the method of placement and compaction, as well as the thickness, and the quality of rock. Current MTO Guidelines provide designers with predicted settlements as a function of embankment height, type and quality of rock and method of placement. The purpose of this study was to gain a better understanding of the actual settlement behaviour (i.e., immediate during construction, short-term, and long-term) of rock fill embankments constructed to typical heights for highway embankments and with typical rock fill and construction methods in Northern Ontario. The project involves 20 m high rock fill embankments that have been instrumented and monitored during and following construction over a four-year period (2017 to 2021). The site is located within Ojibway Canyon near French River in Northern Ontario, which is a part of the new four-laning of Highway 69.

The settlement monitoring instruments include settlement plates (SPs) installed during construction at different depths/heights within the rock fill to measure the magnitude of fill settlements (as well as at the base of the embankments to measure the foundation soil settlements) in relation to fill thickness. In addition, shape accelerometer arrays (SAAs) were installed near the top of the embankment to provide detailed settlement-deflection profiles along the cross-section of the rock fill embankments.

The rock fill embankments were built-up to the underside of the proposed pavement structure from February to June 2017 and remained as such until September 2020 when the 440 mm thick NBL pavement structure, consisting of asphalt and granular subbase and base, was placed over the rock fill. The two-lane traffic from the original highway was switched to the new two-lane NBL embankment in October 2020. In June 2021, the 440 mm pavement structure for the SBL was placed and the four-lane highway was fully opened to traffic in December 2021.

This paper presents the final results of the settlement monitoring program for the 4-year period, from completion of rock fill placement in June 2017 up to April 2021, as an update to Bom et al. (2019) and Varshoi et al. (2017) papers that presented the interim results of this study. In addition, a comparison of the settlement results and estimated required preload times based on the findings from the current study versus the MTO September 2010 Guideline "*Rock Fill Settlement and Rock Fill Quality Estimates*" has been carried out and the conclusions of this comparison are presented herein.

2 BACKGROUND

As presented in Varshoi et al. (2017) and Bom et al. (2019), the Ojibway Canyon site is an approximately 60 m long low-lying area with nearly vertical bedrock faces on each side of the canyon. The new highway at the location of the study required fill embankments up to approximately 20 m high placed over a native, compact to dense sandy soil foundation layer (approximately 0.4 m to 4.7 m thick), over bedrock. Rock fill placement to the underside of the pavement structure was carried out between February and June 2017. The photograph on Figure 1 shows the west slope of the SBL embankment as of April 2021.

Figure 1. Photograph of SBL west slope looking north from south limits in April 2021.

2.1 MTO Guideline for Rock Fill Settlement (September 2010)

The estimation of magnitude of settlement for rock fill embankments for highway design in Ontario is based on an MTO guideline titled, "*Rock Fill Settlement and Rock Fill Quality Estimates*" (MTO, September 2010). The guideline presents methods for estimating the short-term and long-term settlements of rock fill embankments as functions of the rock fill thickness (or height, H) and method of placement (compacted versus dumped). The guideline is understood to be based on typical values for rock fill settlement as commonly used in practice and/or reported in literature, including from the study carried out for the Ontario Ministry of Transportation and Communications, (RR227, 1982). In the guideline, the "short-term" is defined as 1 year after construction of rock fill embankment to full height. The guideline applies to rock fill embankments constructed with strong, granitic-type rock fills that are up to 15 m in total thickness and is not applicable to the design and settlement of highly degradable rock fills such as fissile shales.

The guideline indicates that rock fill shall be placed and compacted in accordance with Ontario Provincial Standard Specification OPSS.PROV 206. Further, the guideline assumes that within six months of the construction to full height, approximately 90 percent of the "short-term" settlement will take place. Table 1 and Table 2 present the "short-term" and "long-term" settlement estimates for rock fill embankments as functions of the rock fill height (H) and placement method as included in the guideline (MTO, September 2010).

Table 1. Short-Term Rock Fill Settlement (MTO, September 2010)

Height of Rock Fill, H (m)	Short-Term Settlement (m)*	
	Compacted Rock Fill	Dumped Rock Fill
Up to 5	0.5% H	1.0% H
> 5 to 10	0.75% H	1.5%H
> 10 to 15	1.0% H	2.0%H

* within 1 year after completion of construction

Table 2. Long-Term Rock Fill Settlement (MTO, September 2010)

Height of Rock Fill, H (m)	Long-Term Settlement (m)**	
	Compacted Rock Fill	Dumped Rock Fill
Up to 15 m	0.1% H	0.2% H

** following 1 year after completion of construction

2.2 Current Specification for Rock Fill Placement

OPSS.PROV 206, Section 206.07.05.02 specifies that during construction, the thickness of each rock fill lift shall not exceed 1.5 m (prior to compaction) and each layer shall be fully compacted before a new lift is added. Further, it states that each lift of rock fill shall be placed in final position by blading without the use of end dumping, except when the rock fill is placed in water, at which time end dumping is acceptable and where compaction of the rock fill is not required. The compaction equipment is specified to consist of a crawler type tractor bulldozer with a minimum of 6 passes and a maximum of 8 passes with a maximum equipment speed specified at 3.2 km/hr. The rock fill is specified to be compacted to minimize voids and bridging of large rock fragments within the embankment.

Section 206.07.05.02 further specifies that the rock fill embankments may be constructed with rock particle size exceeding 1.0 m in any dimension; however, the larger rock sizes shall be well distributed throughout the embankment. The specification allows for rock fragments up to a maximum of 3.0 m in size to be incorporated into the embankment, provided they are sufficiently spaced for compaction equipment to effectively compact the fill layer and provided the oversized rock is appropriately positioned a certain depth from the top of the rock embankment so as not to protrude into the pavement structure.

2.3 MTO Embankment Settlement Criteria for Design (July 2010)

MTO's *"Embankment Settlement Criteria for Design"* (July 2010) specifies the total allowable post-construction settlement during the pavement design life. To satisfy the allowable post-construction settlement criteria as specified in the July 2010 guideline, preloading of the rock fill embankment may be required and therefore needs to be assessed as part of design.

MTO also specifies the design life of the embankment to be 20 years following construction of the pavement structure for King's highways; and 15 years following construction of the pavement structure for secondary highways (July 2010). However, based on the results of the long-term (creep) rock fill settlement assessment from the current study, it is suggested that a shorter design life could be considered that gives due consideration to the typical asphalt pavement design life and typical pavement rehabilitation periods; this will be discussed further in Sections 4.2 and 5.

For the assessment of preload times for this study, only distances of 0 m to 20 m and ≥75 m from a bridge (most and least stringent in the criteria) have been considered for freeways and non-freeways, as presented in Table 3, as specified in Table 1.2 of MTO's criteria (July 2010).

Table 3. Post-Construction Settlement Criteria (MTO, July 2010)

Distance from Transition Point	Maximum Limits During Pavement Design Life	
	0 m - 20 m	≥75 m
Freeways	25 mm	100 mm
Non-Freeways	25 mm	200 mm

2.4 Ojibway Canyon Monitoring Program and Embankment Construction

The settlement monitoring program at the site was carried out at three areas of the rock fill embankment construction. Different rock fill placement/compaction techniques were utilized within each of the three settlement monitoring areas, as follows:

- Area 1 is within the southern 30 m footprint of the NBL embankment with rock fill placed and compacted in accordance with OPSS.PROV 206 (maximum 1.5 m thick lifts compacted with tractor bulldozer with 6 to 8 passes);
- Area 2 is within the northern 30 m footprint of the NBL embankment with rock fill placed in accordance with OPSS.PROV 206 (maximum 1.5 m thick lifts) but compacted by a vibratory drum roller with a minimum operating mass of 10,000 kg and a minimum dynamic force of 90 kN (tractor bulldozer still used to grade/blade each lift); and,
- Area 3 is within the 60 m footprint of the SBL with rock fill sizes in accordance with OPSS.PROV 206 but with no maximum lift thickness and no specified compactive effort; however, it is noted that some amount of compaction of the rock fill occurred near the centreline due to the contractor using a portion of the embankment as a haul road.

Varshoi et al. (2017) presented a schematic showing the detailed layout of the instruments for the settlement monitoring program at each of the three areas; at each area there was one full depth settlement plate (FDSP), several settlement plates (SPs) at different layers/heights within the rock fill embankment, shallow SPs and one Shape Accelerometer Array (SAA).

3 RESULTS OF MONITORING

The construction of the SBL and NBL rock fill embankments started on January 31 and February 6, 2017, respectively. Filling was completed on May 25 and May 30, 2017 for the SBL and NBL embankments, respectively. The monitoring data (where available at the instruments that survived the construction and full monitoring period including opening of the highway to traffic) were taken up to April 7, 2021.

In September 2020, the SPs for the NBL embankment in Areas 1 and 2, were removed as part of the NBL pavement structure construction and several SPs in Area 3 for the SBL embankment had been destroyed by the Contractor. The SAAs in all three monitoring areas remained functional up to the end of the long-term monitoring assignment, in addition to several SPs in Area 3.

A typical plot of the settlement data collected in Area 1, where the rock fill was placed and compacted by tractor bulldozer as per OPSS 206 is shown plotted versus linear time in Figure 2. The sequence of rock fill placement as depicted by the fill thickness versus time is also shown in the figure.

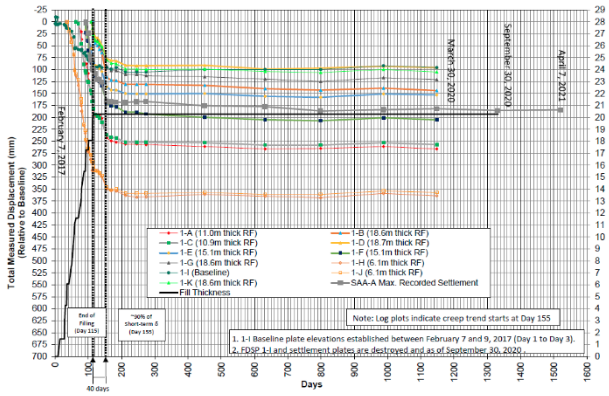

Figure 2. Area 1 – Total rock fill settlement and fill thickness versus time for SPs and SAA.

In order to evaluate the data and distinguish between short-term settlement (i.e. immediately after completion of filling) and long-term (i.e. creep) settlement, the monitoring data from each of the three areas was corrected to discount the foundation soil settlement and the net rock fill settlement plotted versus log-time in Figures 3, 4 and 5 for Areas 1, 2 and 3, respectively.

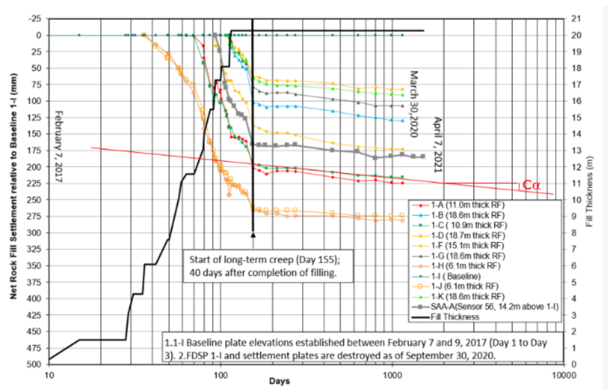

Figure 3. Area 1 – Net rock fill settlement versus log-time for SPs and SAA.

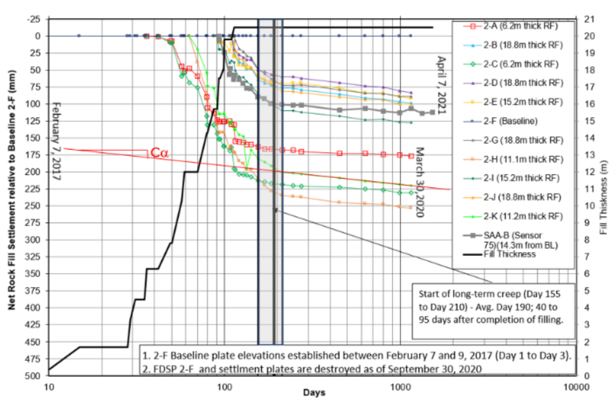

Figure 4. Area 2 – Net rock fill settlement versus log-time for SPs and SAA.

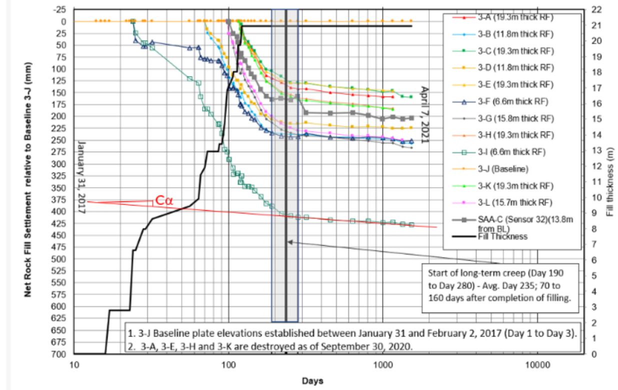

Figure 5. Area 3 – Net rock fill settlement versus log-time for SPs and SAA.

4 DATA INTERPRETATION

The following sections discuss the interpretation of the settlement data collected for Areas 1, 2 and 3 in the context of the magnitude of settlement as function of the rock fill thickness. The evaluation of the data has been separated into: 1) short-term settlement measured (immediately after construction); 2) long-term, post-construction (or creep) settlement; and, 3) preload time estimates to satisfy MTO embankment settlement criteria. The evaluation of the rock fill settlement data measured during construction was presented in Bom et al. (2019).

4.1 Short-Term Settlement

The short-term rock fill settlement was evaluated based on the survey measurements at the SPs, installed at different heights within the rock fill embankments, in the period from immediately after completion of fill placement to start of long-term settlement (i.e., creep). The semi-log plots, as shown in Figures 3, 4 and 5 (for Areas 1, 2 and 3, respectively), were used to define the start of the long-term (creep) trend for each of the monitoring areas. The point of intersection of the long-term (creep) trend with the earlier settlement versus time data was defined as the end of the short-term settlement period. In Area 1, almost all the SPs and the SAA showed the same day for end of short-term settlement (i.e., 40 days), presumably as a result of a relatively uniform method of rock fill placement and compaction (i.e. in accordance with OPSS.PROV 206). However, in Areas 2 and 3, the SPs and SAAs showed a wider range for the end of short-term settlement (i.e., varying by as much as 55 days in Area 2 and 90 days in Area 3), suggesting significantly more variability in the method of rock fill placement and compaction or lack thereof. Table 4 presents a summary of the duration of short-term settlement for Areas 1, 2 and 3.

Table 4. Short-Term Rock Fill Settlement Duration (Current Study)

Settlement Monitoring Area	Short-Term Settlement Duration
Area 1	40 days
Area 2	40 to 95 days (average 70 days)
Area 3	70 to 160 days (suggest 180 days)[1]

[1]Time for end of short-term settlement in Area 3 is difficult to assess because the range of short-term settlement duration is affected by the variable degrees of compactive effort in this area. A time frame higher than the 70 to 160 day range is suggested due to the variability of the uncompacted rock fill and the potential influence/compaction of the haul road affecting the time rate settlement measurements at Area 3.

The data indicates that the short-term settlement occurs relatively quickly and is finished within about 40 days to 95 days following completion of filling for compacted rock fill (Areas 1 and 2, respectively), and is finished within about 70 days to 160 days following completion of filling for dumped rock fill (Area 3). There is some uncertainty regarding the rate of settlement of the dumped rock fill in Area 3, given that a portion of this embankment was used as a haul road by the contractor and as such, would have experienced some degree of compaction; in our opinion, the longer duration in the range (i.e., suggested as 180 days) is likely more representative for the uncompacted rock fill. The time frame for the duration of short-term settlements for rock fill placed and compacted in accordance with OPSS.PROV 206 (i.e., suggested as 60 days) is significantly less than that recommended in the MTO guideline (September 2010).

It is noted that the duration for the completion of the short-term rock fill settlement is important, as it delineates the starting point for the calculation of the long-term (or creep) rock fill settlement, as discussed in Section 4.2 and also affects the duration of the preload.

With the end of short-term settlement 'Day' defined, both the magnitude and duration of the short-term settlement at each settlement plate location (i.e., height within the rock fill embankment) were calculated. Table 5 presents minimum, maximum and average values of the net short-term rock fill settlement as a function of the rock fill thickness/embankment height (H).

Table 5. Short-Term Rock Fill Settlement (Current Study)

Settlement Monitoring Area	Embankment Height (m)	Short-Term Settlement[1,2]		
		Min	Average	Max
Area 1	0 to 10	0.13% H	0.18% H	0.21% H
	10 to 20	0.28% H	0.35% H	0.45% H
Area 2	0 to 10	0.17% H	0.27% H	0.36% H
	10 to 20	0.18% H	0.27% H	0.35% H
Area 3	0 to 10	0.26% H	0.51% H	0.68% H
	10 to 20	0.54% H	0.72% H	0.77% H

[1]The normalized short-term settlements for embankment heights of 0 m to 10 m are considered to be conservative due to the surcharge loading of the upper rock fill embankment.

[2]Settlement as a function of rock fill thickness (H).

The data indicates that for the rock type and embankment heights at this site and compacted in accordance with the OPSS.PROV 206, the settlement of rock fill that takes places in the short-term (immediately after construction) ranges from approximately 0.1%·H to 0.5%·H. The data also suggests that the short-term settlement of the uncompacted rock fill ranges from 0.3% to 0.8% of the total rock fill thickness. These short-term settlements are lower (i.e., by 50% or more) than that recommended in the MTO guideline (September 2010) for both compacted and dumped rock fill, as presented in Table 1.

For rock fill placed and compacted in accordance with OPSS.PROV 206 (Area 1), it appears that assuming short-term settlements equal to 0.3%·H for fill heights up to 10 m, and 0.5%·H for fill heights up to 20 m would be a conservative assumption. For dumped rock fill placed without any control on compaction (Area 3), the data suggests that assuming short-term settlements equal to 0.7%·H for fill heights up to 10 m, and 0.8%·H for fill heights up to 20 m would be a reasonable assumption; however, given the uncertainties associated with the actual level of compaction in Area 3, it is suggested that somewhat more conservative estimates of 0.8%·H for fill heights up to 10 m, and 1.0%·H for fill heights up to 20 m be considered. These values are significantly less than the amounts recommended in the MTO guideline (September 2010) for the evaluation of short-term settlement of compacted and dumped (i.e., uncompacted) rock fill.

The average net short-term settlements, measured by comparing net settlements in different sets of SPs at different heights and net settlements in SPs near the top of the embankment fill, in each of the monitoring areas have been normalized to vertical strain for the rock fill embankment height and plotted on Figure 6, along with the short-term settlement recommendations in the MTO guideline (September 2010) for comparison.

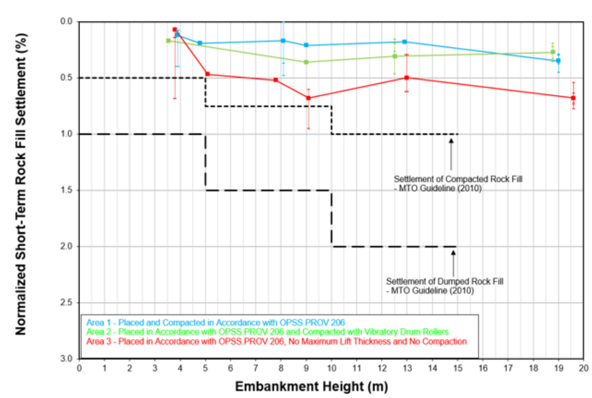

Figure 6. Normalized Short-Term Rock Fill Settlements vs. Embankment Height.

4.2 Long-Term Settlement

To evaluate the settlement occurring in the long-term (i.e., after completion of the short-term settlement), a straight line was fit to the long-term settlement trends shown on the semi-log plots in Figures 3, 4 and 5. This was carried out for each of the shallowest (highest elevations) SPs and SAAs to check the range of slope(s) of the trend lines for each of the three areas. The slope of the trend lines was then used to calculate $C\alpha(\varepsilon)$ values representative of the creep settlement in terms of log-cycles of time following completion of the short-term settlement. Table 6 summarizes the results of this interpretation.

Table 6. Long-Term Rock Fill Settlement (Current Study)

Settlement Monitoring Area	Suggested Start of Start of Long-Term Settlement	Long-Term Settlement[1] (per log-cycle of time)		
		Min	Average	Max
Area 1	40 days	0.13% H	0.15% H	0.17% H
Area 2	70 days	0.13% H	0.15% H	0.16% H
Area 3	180 days[2]	0.17% H	0.17% H	0.22% H

[1]Settlement per log-cycle of time (after completion of short-term settlement) as a function of rock fill thickness (H) for rock fill embankment heights up to 20 m.

The data indicates that for the rock type and embankment heights at this site, the creep settlement of rock fill that takes place in the long-term, ranges from about 0.1%·H to 0.2%·H per log-cycle of time following completion of short-term settlement to the design life.

For rock fill with heights up to 20 m, placed and compacted in accordance with OPSS.PROV 206 (Area 1), it appears that assuming long-term creep settlements equal to about 0.15%·H per log-cycle of time would be a reasonable (average) assumption. Long-term settlement (i.e., creep rates) for compacted rock fill is greater (by about 50% on average) than the amount recommended in the MTO guideline (September 2010).

For uncompacted rock fill with heights up to about 20 m (Area 3), it appears that assuming long-term settlements equal to about 0.2%·H per log-cycle of time would be a reasonable (conservative) assumption. Given the potential for some compactive effort in Area 3, due to the contractor using a portion of the embankment for a haul road, it is suggested that a creep value near the higher end of the range (and not the average) be considered more representative of the dumped/less compacted rock fill.

The current MTO guideline (September 2010) does not express the long-term rock fill settlement in terms of log-cycles of time and simply states that the creep settlement is expected to occur from the end of the short-term settlement over the life of the embankment. The long-term (creep) settlement for all geomaterials (i.e., for organic soils, for mineral soils, and for rock fill) is typically expressed as occurring over log-cycles of time and the data collected from this study supports this methodology. As such, it is suggested that the design for long-term rock fill settlement take into consideration the total time frame over which the long-term (creep) settlement is of interest (i.e., from the end of the short-term settlement to the end of the design life of the embankment or pavement structure). For example, for compacted short-term rock fill settlement completed in 60 days following completion of filling, if it is assumed that the typical design life for a pavement structure is about 10 years (3,650 days), then approximately two log-cycles of time (i.e., log 3650 - log 60 = 1.8 log cycles) should be considered in the calculation of the magnitude of rock fill creep settlement. This approach (i.e., in terms of number of log cycles of time) results in an overall larger magnitude of the long-term creep settlement than what would be otherwise calculated using the current MTO guideline (September 2010). The additional creep settlement, however, would be offset by the relatively smaller magnitude(s) of short-term settlement that are suggested based on the results of this study.

4.3 Rock Fill Preload Time Estimates

To compare the affects of the MTO rock fill settlement guideline (September 2010) with the results of the settlement monitoring assessment and associated suggestions for rock fill settlement from the current study, an assessment of the duration of the preload times that would be required to satisfy the MTO's post-construction settlement criteria (MTO July 2010) for distances of 0 m to 20 m and ≥75 m from a bridge have been considered for freeways and non-freeways. (Section 2.3, Table 3).

The preload times required to achieve MTO's specified post-construction settlement (July 2010) have been assessed for 10 m, 15 m and 20 m embankment heights for both compacted and dumped rock fill for a 10-year and 20-year embankment design life. The actual required preload times for each embankment would need to be assessed on an project specific basis by the foundation designer in conjunction with the highway/bridge designer and MTO, including for transitions between 20 m and 75 m from a bridge as specified in Table 1.2 of MTO's settlement criteria (July 2010), considering the acceptable risk tolerance for post-construction settlement after construction of the embankment.

Tables 7, 8 and 9 present the required preload times to comply with MTO's settlement criteria (July 2010) of: 1) 25 mm within 20 m of a bridge; 2) 100 mm for a freeway greater than 75 m from a bridge abutment; and, 3) 200 mm for a non-freeway greater than 75 m from a bridge, respectively. The three tables present a comparison based on the rock fill settlement estimates from MTO's guideline (September 2010) and the current study, based on an assumed 10-year embankment design life.

Table 7. Estimated Preload Time to Satisfy 25 mm Post-Construction Settlement within 20 m of a Bridge

Height of Rock Fill Embankment H	Compacted or Dumped	Estimated Preload Time for 10-Year Embankment Design Life (Days)	
		MTO (Sept. 2010)	Current study
10 m	Compacted	160	80
	Dumped	300	200
15 m	Compacted	220	**280**
	Dumped	900	540
20 m	Compacted	320	**540**
	Dumped	1,600	860

For 25 mm total post-construction settlement within 20 m of bridge, preloading is required for 10 m, 15 m and 20 m high compacted and dumped rock fill embankments. The results from the current study suggest that in most cases less preload time is required in the construction schedule as compared with what would be calculated using the MTO's current (September 2010) guideline. For dumped embankments, the results from the current study indicate a decrease in the required preload time compared to MTO's guidelines by 50% to 70% for 10 m, 15 m, and 20 m high embankments for a 10-year design life. For 10 m high embankments (which are arguably the most common embankment heights on MTO projects) the results from the current study indicate a decrease in the required preload time compared to MTO's guidelines by 50% for a 10-year design life for both compacted and dumped rock fill. However, for compacted rockfill, the results from the current study indicate an increase in the required preload time compared to MTO's current guidelines by 40% to 60% for 15 m and 20 m high embankments.

Table 8. Estimated Preload Time to Satisfy 100 mm Post-Construction Settlement for a Freeway ≥ 75 m from a Bridge

Height of Rock Fill Embankment H	Compacted or Dumped	Estimated Preload Time for 10-Year Embankment Design Life (Days)	
		MTO (Sept. 2010)	Current Study
10 m	Compacted	0	0
	Dumped	90	14
15 m	Compacted	70	0
	Dumped	150	100
20 m	Compacted	120	30
	Dumped	170	140

For 100 mm total post-construction settlement for freeways greater than 75 m from a bridge, based on the results of the current study, preloading is only required for 15 m dumped and 20 m high compacted and dumped rock fill embankments as compared with MTO's (September 2010) guideline method which would require preloading for 10 m high dumped and 15 m and 20 m high compacted and dumped embankments. For dumped embankments, the results from the current study indicate a decrease in the required preload time compared to MTO's guidelines by 20% to 30% for 15 m, and 20 m high embankments. Based on the results of the current study, the requirements for preloading would be about 2 weeks for 10 m high embankments. For compacted embankments, the results from the current study indicate a decrease in the required preload time compared to MTO's guidelines by 30% for 20 m high embankments. Based on the results of the current study, the requirements for preloading would be eliminated for 10 m and 15 m high embankments.

Table 9. Estimated Preload Time to Satisfy 200 mm Post-Construction Settlement for a Non-Freeway ≥ 75 m from a Bridge

Height of Rock Fill Embankment H	Compacted or Dumped	Estimated Preload Time for 10-Year Embankment Design Life (Days)	
		MTO (Sept. 2010)	Current Study
10 m	Compacted	0	0
	Dumped	0	0
15 m	Compacted	0	0
	Dumped	70	0
20 m	Compacted	20	0
	Dumped	120	50

For 200 mm total post-construction settlement for non-freeways greater than 75 m from a bridge, based on the results of the current study, preloading is only required for 20 m high dumped rock fill embankments, and compared to MTO's (September 2010) guideline method for the same embankment, the required preloading time was decreased by approximately 60%. Preloading is required for MTO's method for 15 m high dumped embankments and 20 m high compacted and dumped rock fill embankments.

The settlement and preload estimates for 10 m, 15 m and 20 m compacted and dumped rock fill embankments were plotted and a typical plot for the 10 m compacted embankment is presented in Figure 7.

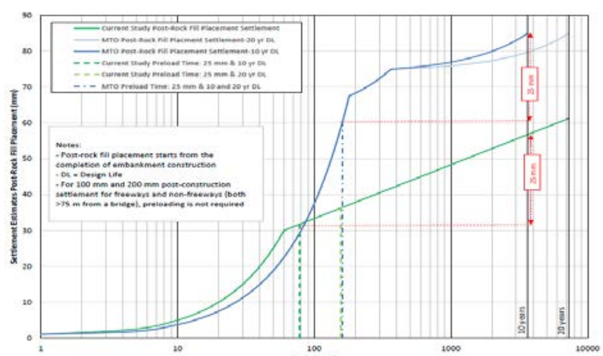

Figure 7. Settlement Estimates Post-Rock Fill Placment and Preload Times for 10 m Compacted Embankment

5 SUMMARY OF STUDY FINDINGS

Based on an assessment of the immediate (i.e., during construction), short-term, and long-term (i.e., up to 4 years post-construction) rock fill settlement monitoring carried out at this site, the following is a summary of the findings for the type of rock fill and embankment heights in the current study.

- For rock fill placed and compacted in accordance with OPSS.PROV 206, it appears that assuming immediate rock fill settlement (i.e., that occurring during rock fill placement) equal to about 2%·H (where H=rock fill height) would be a conservative assumption.
- For uncompacted/dumped rock fill, it appears that assuming immediate rock fill settlement (i.e., that occurring during rock fill placement) equal to about 3%·H would be a conservative assumption.
- For rock fill placed and compacted in accordance with OPSS.PROV 206, it appears that assuming short-term settlements equal to 0.3%·H for fill heights up to 10 m, 0.4%·H for fill heights up to 15 m, and 0.5%·H for fill heights up to 20 m would be a conservative assumption.
- For uncompacted/dumped rock fill, given the uncertainties associated with the potential for some level of compaction to have occurred in Area 3, it is suggested that short-term settlements be conservatively estimated as being equal to 0.8%·H for fill heights up to 10 m, 0.9%·H for fill heights up to 15 m, and 1.0%·H for fill heights up to 20 m.
- For rock fill placed and compacted in accordance with OPSS.PROV 206, it appears that assuming short-term settlements are completed within two months (60 days) would be a reasonable/conservative assumption.
- For uncompacted/dumped rock fill placed without any control on compaction, it appears that assuming short- term settlements are completed within six months (180 days) would be a conservative assumption.
- For rock fill with heights up to 20 m, placed and compacted in accordance with OPSS.PROV 206, it appears that assuming long-term creep settlements equal to about 0.15%·H per log-cycle of time (after completion of the short-term settlement, 2 months) would be a reasonable (average) assumption.
- For uncompacted/dumped rock fill with heights up to about 20 m, it appears that assuming long-term settlements equal to about 0.2%·H per log-cycle of time (after completion of the short-term settlement, 6 months) would be a reasonable (conservative) assumption.

The above suggestions based on interpretation of the results of this study are summarized in Tables 10 and 11 below:

Table 10. Current Study's Suggested Short-Term Settlement

Height of Rock Fill Embankment, H (m)	Current Study's Suggested Short-Term Settlement (m) [1]	
	Compacted Rock Fill	Dumped Rock Fill
10 m	0.3%·H	0.8%·H
15 m	0.4%·H	0.9%·H
20 m	0.5%·H	1.0%·H

[1]The current study indicates short-term settlements are completed within two months (60 days) for compacted rock fill and within six months (180 days) for uncompacted/dumped rock fill placed without any control on compaction.

Table 11. Current Study's Suggested Long-Term Settlement

Height of Rock Fill Embankment, H (m)	Current Study's Suggested Short-Term Settlement (m) [1]	
	Compacted Rock Fill	Dumped Rock Fill
Up to 20 m	0.15%·H per log-cycle of time	0.2%·H per log-cycle of time

[1]Suggested time for start of long-term rock fill settlement is 60 days (2 months) for compacted rock fill and 180 days (6 months) for uncompacted/dumped rock fill placed without any control on compaction

ACKNOWLEDGEMENTS

The writers would like to acknowledge the support from MTO Northeast Region, AECOM Canada as the Contract Administrator, and Peto MacCallum Ltd for the detail design for the instrumentation.

References:

Bom, A., Dittrich, J.P., Varshoi, A., De Souza, A.K., Sangiuliano, T., and Ahmad, K. 2019. Update on Rock Fill Settlement in a Highway Embankment in Northern Ontario: A Case Study. 72nd *Canadian Geotechnical Conference.* St. John's, Ontario.

Canadian Foundation Engineering Manual. 2006. Fourth Edition. Canadian Geotechnical Society.

Farhangi, S., Ritchie, D. and Verma, N.S. 2014. Rockfill Compaction Trial. *67th Canadian Geotechnical Conference.* Regina, Saskatchewan.

Ministry of Transportation, Ontario. July 2010. MTO Embankment Settlement Criteria for Design.

Ministry of Transportation, Ontario. September 2010. MTO Guideline for Rock Fill Settlement and Rock Fill Quantity Estimates.

Ministry of Transportation and Communications. 1982. RR227 Rockfill in the Foundation Design of Highway Structures by Dr. K. Y. Lo.

Ministry of Transportation, Ontario. 2013. Ontario Provincial Standard Specification, OPSS.PROV 206, Construction Specification for Grading.

Varshoi, A., Bom, A., Dittrich, J.P., Thibeault, M., Sangiuliano, T., Nascimento, C.M.P. and Ahmad, K. 2017. Rock Fill Settlement in a Highway Embankment in Northern Ontario: A Case Study. *70th Canadian Geotechnical Conference.* Ottawa, Ontario.