Update on Rock Fill Settlement in a Highway Embankment in Northern Ontario: A Case Study

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ABSTRACT

This paper presents an update on the results of the ongoing settlement monitoring program at three sections of a 20 m high rock fill embankment in Ojibway Canyon along the new Highway 69, near French River in Northern Ontario. Three different methods of rock fill placement/compaction were employed at three sections of the embankment(s), including a placement/compaction method in accordance with the current Ontario provincial specification (OPSS.PROV 206). The construction of the rock fill embankment(s) was carried out between February and May 2017 and the settlement monitoring was carried out during and following construction. The purpose of the settlement monitoring, planned to continue for up to four years after completion of construction, is to validate a current MTO Guideline for estimating short-term and long-term settlements within rock fill embankments and to study the impact of placement/compaction methods on rock fill settlement. The settlement instrumentation includes: (i) settlement plates installed at different depths/heights within the rock fill embankment to measure the magnitude of fill settlements (as well as foundation soil settlements); and (ii) shape accelerometer arrays to provide a settlement-deflection profile across the entire cross-section of the rock fill embankment(s). Measurements have been taken at specified intervals of time to evaluate the short- and long-term settlement behaviour of the rock fill embankment(s). The preliminary results of the settlement monitoring data collected during construction (up to May 2017) were previously presented at GeoOttawa 2017. This paper presents and interprets the short-term (immediately after construction) and long-term (creep), post-construction monitoring data collected between June 2017 and April 2019, provides a comparison to the current MTO Guideline for estimating rock fill settlements, and includes a discussion on considerations for future versions of the MTO Guideline.

RÉSUMÉ

Ce document présente une mise à jour des résultats d'un programme de surveillance du tassement de remblai rocheux d'une hauteur de 20m, dans le canyon Ojibway sur la nouvelle autoroute 69, près du secteur de la rivière des Français dans le nord de l'Ontario. Trois méthodes différentes de mise en place et de compaction du remblai ont été employés sur trois sections du talus. Une des trois méthodes utilisées, suivait la réglementation provinciale de l'Ontario (OPSS.PROV 206). La mise en place du(des) remblai(s) rocheux a été faite entre les mois de février et mai 2017. Le suivi du tassement à été faite pendant et suivant la période de construction et pour valider les lignes directrices du ministère des transports de l'Ontario quant aux estimations à court et à long terme du tassement des remblais rocheux et pour étudier les impacts de différentes méthodes de mise en place et de compaction sur le tassement des remblais rocheux. Le programme de surveillance, comprend: (i) des plaques de tassement installées à différentes profondeurs à l'intérieur du remblai pour mesurer l'ampleur des changements causer par le tassement dans le remblai rocheux et des sols de fondation. Les plaques de tassement ainsi (ii) qu'une matrice d'accéléromètres permettent la création d'un profile de tassement-déflection pour une coupe transversale du talus composés de remblai rocheux. Les mesures ont été prise à des intervalles spécifiés afin de pouvoir mesurer les changements à court et à long terme à l'intérieur du(des) remblai(s) rocheux. Les résultats préliminaires collectés pendant la construction (jusqu'à juin 2017), ont été présenté à GeoOttawa 2017. Ce papier présente et interprète les résultats du programme de surveillance à court terme (immédiatement après la construction) et à long terme après la fin des travaux, entre juin 2017 et avril 2019. Il fournit aussi une comparaison des standards actuels du ministère des transports de l'Ontario, qui sont utilisés pour estimer le tassement dans les remblais rocheux. Il présente aussi des considérations pour les versions futures des linge directrices du ministère des transports de l'Ontario.

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 (on the order of several per cents of the fill height) depending on the method of placement and compaction, as well as the thickness, and the quality of rock. While the settlement analysis for natural soils is routinely carried out based on conventional theoretical methods (e.g., elastic theory, consolidation theory, etc.), the method of analysis for the prediction of rock fill settlement is generally empirical and based on correlations developed from settlement measurements at existing projects, typically obtained from rock fill dams. As such, much of the data available in literature is based on rock fill heights of 50 m to 100 m. The applicability of the extrapolation of the data from these projects to typical highway embankment heights (up to 20 m high, but generally less than 10 m) is unknown. Further, based on a comparison of settlements from over 80 rock fill dams, Milligan and Coyne (2005) concluded that using a single general formula to predict deformations within rock fills is not reliable due to the great number of variables that affect the settlement, such as porosity, size, angularity and quality of rock fill particles; and method of construction including thickness of lifts and number of passes. Milligan and Coyne (2005) also indicate settlement of rock fill is not only short-term and elastic, but can continue over the long-term due to degradation, local crushing and/or movement of the rock fill particles. Therefore, the validity of developing correlations to estimate rock fill settlement based on data from case studies involving different rock types, compaction methods, rock fill heights, lift thicknesses, site geometry, etc. is unknown and needs to be studied.

The purpose of this study is to gain a better understanding of the actual settlement behaviour (i.e., 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 Ontario. The project involves 20 m high rock fill embankment(s) that have been instrumented and monitored during and following construction over the past 2 years (2017 to 2019). 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. A description of the site and preliminary results of the settlement measured during embankment construction from February to May 2017, were presented in Varshoi et al. (2017).

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 (SAA) were installed in May 2017 (near the end of construction) to provide a settlement-deflection profile along the cross-section of the rock fill embankment(s).

The rock fill embankment was built up to the underside of the proposed pavement structure in June 2017 and since then, no new fill has been placed. By late 2019/early 2020, a 440 mm thick pavement structure, consisting of asphalt and granular subbase and base, is scheduled to be placed on the Northbound Lane (NBL) embankment and by 2021, the same pavement structure will be placed on the Southbound Lane (SBL) embankment.

This paper presents results of the settlement monitoring program for a 2-year period, from completion of rock fill placement in June 2017 up to April 2019. The overall monitoring program is planned for a total of four years and as such, it is anticipated that about 2 more years of long-term (creep) rock fill settlement data will still be collected.

2 BACKGROUND

The Ojibway Canyon site is an approximately 60 m long low-lying swamp with nearly vertical bedrock faces on each side of the canyon. The new highway at the location of the study requires fill embankments up to approximately 20 m high placed over a 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 2019.

Figure 1. Photograph of SBL west slope looking south from north limits in April 2019.

2.1 Current MTO Guideline for Rock Fill Settlement

As discussed in Varshoi et al. (2017), 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, 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 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 (including both above and below water). 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 per cent 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 thickness and placement method as included in the guideline (MTO, 2010).

Table 1. Short-Term Rock Fill Settlement

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

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 stated 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 shall 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 Ojibway Canyon Monitoring Program and Embankment Construction

The settlement monitoring program at the site is being carried out at three areas of the rock fill embankment. 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.

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 which are summarized here as follows:

- One full depth settlement plate (FDSP) in each of the three areas founded on the native sand subsoil at base of rock fill embankment to monitor settlement of the foundation soil;
- Two settlement plates (SPs) founded within the lower portion of the rock fill in each of the Areas 1, 2 and 3 underlain by an approximately 6.1 m, 6.3 m and 6.6 m thick layer of rock fill, respectively;
- Two SPs founded within the middle of the rock fill in each of the Areas 1, 2 and 3 underlain by an approximately 11.8 m, 11.6 m and 11.9 m thick layer of fill, respectively;
- Two SPs founded within the upper portion of the rock fill in each of the Areas 1, 2 and 3 underlain by an approximately 15.3 m, 15.1 m and 16.9 m thick layer of rock fill, respectively;
- Three horizontal Shape Accelerometer Arrays (SAA) installed across the entire cross-section in each of the Areas 1, 2 and 3 underlain by an approximately 14.2 m, 14.2 m and 13.5 m thick layer of rock fill, respectively; and,
- Four to five shallow SPs founded near the surface of the rock fill embankment in each of the three Areas 1, 2 and 3 underlain by an approximately 18.6 m, 18.8 m and 19.3 m thick layer of rock fill, respectively.

The Contractor was requested to provide feedback regarding the rock fill placement for the three areas. Due to the small test area (about 60 m in length), the canyon presented many challenges for accessibility for the Contractor. Specifically, the placement method at Area 2 was least preferred by the Contractor due to the additional effort to level the site as much as possible prior to application of smooth drum vibratory roller and the reported strain on the roller operator. There were also negative impacts to the vibratory roller compacting the relatively dense to very dense rock fill (i.e. roller breakdowns). Given the difficulties reported by the Contractor associated with the use of the vibratory roller, the actual level of compaction achieved in Area 2 is unknown. In Area 3, uncontrolled “end-dumping” of rock fill was not possible due to the logistics associated with the size and access to this area. In addition, the use of some track equipment was required in Area 3 to level each lift to facilitate the approximately 1.5 m rod extensions (similar to Area 1 and 2) as well as to create a level road for access/hauling through the canyon. The method of rock fill placement in Area 1 (in accordance with OPSS.PROV 206) was the most preferred by the Contractor.

As discussed in Section 4, the settlement data and interpretation of the results presented herein is for rock fill embankments comprised of granitic or gneissic parent rock and as such the results are likely not applicable to the design and settlement of highly degradable rock fills such as fissile shales.

3 LITERATURE REVIEW

Varshoi et al. (2017) presented a summary on the theory of rock fill settlement, including that the immediate (short-term) settlement of rock fill is understood to be a result of the elastic deformation of the particles as well as due to the slippage and sliding of particles over one another, while the post-construction (long-term, creep) settlement of rock fill is generally a result of the crushing of particles and particle reorientation/rearrangement.

The following sections discuss the findings of two studies on the settlement of rock fills as they apply to embankments.

3.1 Rock Fill Compaction Trial – Northern Ontario

A rock fill compaction trial was completed at Detour Gold mine, within the Canadian Shield north of Cochrane in Northern Ontario, using mine waste rock extracted during open pit development, placed over a well compacted base (Farhangi et al., 2014). The trial compared the settlement of rock fill compacted using fully loaded mine haul trucks to rock fill compacted with a vibratory smooth drum compactor for 1.5 m, 3.0 m and 4.5 m lift thicknesses. The results of the study indicate that for a control strip completed with 6 passes by the compactor in one 1.5 m thick lift, settlement during construction was 3.7% of lift thickness. After 6 passes with the loaded haul truck over a 1.5 m thick lift, settlement during construction was 7.2% of lift thickness compared with 5.3% for similar 1.5 m thick lift with 2 passes of the loaded haul truck. To achieve similar settlement of 3.7% as the 1.5 m control strip compacted by the compactor, 4 to 6 passes were required with the loaded haul truck for a 3 m thick pad; however, 8 to 10 passes were required for the 4.5 m thick pad. Three main conclusions were identified: 1) fully loaded haul trucks provide greater compaction effectiveness than the compactor, 2) lifts greater than 3 m are not recommended due to “arching and interlocking” of rock fill particles, reducing effectiveness of compaction, and, 3) where limited access is available, dozers and compactors are still required. The results of this study also suggest that for compacted rock fills (i.e., not dumped) a higher level of compactive effort will result in a larger amount of rock fill settlement during construction.

3.2 Rock Fill in Design of Highway Structures

A study was carried out for the Ontario Ministry of Transportation and Communications in 1982 to evaluate (in part) the magnitude of settlements associated with rock fill used in the construction of highway embankments (RR227, 1982). The work is based on an extensive literature review of laboratory testing on rock particles and case studies of field measurements of the settlement behaviour of rock fills constructed primarily for large dams (i.e. heights ranging from 40 m to 100 m). The study considers rock fill settlements that occur during construction or in the short-term immediately after construction but focuses on the long-term, post-construction settlement. The relevant findings are as follow:

i. For compacted rock fill dams, the long-term settlement ranges from 0.02% to 0.2% of the fill thickness (per log-cycle of time *after completion of construction*) with an average of about 0.1%.
ii. For end-dumped rock fill dams, the long-term settlement shows a higher degree of variability and ranges from 0.11% to 0.6% of the fill thickness (per log-cycle of time) with an average of about 0.3%.
iii. For fill heights of interest in highway embankments (say 20 m), extrapolation of the data from the dams indicates that the long-term settlement would be 0.01% of the fill thickness (per log-cycle of time) for compacted rock fill and 0.07% of the fill thickness (per log-cycle of time) for end-dumped rock fill.
iv. Post-construction settlements for end-dumped rock fill are larger than for compacted rock fill and can be substantial if layer thicknesses are larger (say >3 m).
v. Post-construction settlements for compacted rock fill of sound, well-graded rocks, of heights applicable to highway embankments (say, 20 m high) may be neglected.

The results from these literature reviews will be compared to the results interpreted from the settlement monitoring data at this site in the Discussion and Conclusions in Section 7.

4 GEOLOGICAL REVIEW AND COMPRESSIVE STRENGTH TESTING OF ROCK PARTICLES

Since a major component of rock fill settlement can be due to the crushing of particles, a review of the rock type and quality used for construction at the site is considered appropriate to the overall evaluation of the settlements observed. In this regard, during the construction, the following was carried out:

- The rock face at the rock fill source (borrow area) located near the site was reviewed by a geologist to provide a description of the rock face/excavated material related to bedrock classification, jointing and minerology; and,
- Uniaxial Compressive Strength testing (ASTM D7012-14) was completed on five (5) 50 mm diameter by 100 mm long blast rock fill core samples to assess the uniaxial compressive strength of the rock fill.

The bedrock in the rock fill source area generally consisted of medium to coarse grained, felsic to intermediate gneiss, from the Central Gneiss Belt of the Grenville Geological Province. Joints were observed to be generally rough with iron staining noted at select locations. The photograph shown on Figure 2 depicts the geological review at one of the borrow sources. The photograph on Figure 3 shows the five samples selected from the borrow source and used for strength testing.

Figure 2. Bedrock cut along future highway at borrow source of Ojibway.

Figure 3. Samples collected at the site for coring and UCS testing on select samples.

The uniaxial compressive strength completed on the five rock core samples ranged from 65 MPa to 136 MPa, indicating that the bedrock is strong (50 ≤ R4 < 100 MPa) to very strong (100 MPa < R5 < 250 MPa) in accordance with Table 3.5 of Canadian Foundation Engineering Manual (2006).

Degradation of blast rock fill utilized in embankment construction can be caused by either: (i) mechanical degradation, which will apply to the lower zone of blast rock within the embankment due to the loading conditions from the embankment itself; and (ii) weathering degradation of the outer zone of the embankment exposed to the elements. Mechanical degradation is expected to be greater for material that has undergone hydrothermal alteration (which was observed in only one of the samples). Degradation due to weathering will be marginally higher in rocks that contain greater proportions of mafic minerals (dark coloured iron and magnesium rich), such as chlorite, biotite, pyroxene which tend to break down faster when exposed or where strong jointing exists that allows penetration of water and therefore oxidation.

In general, only minor amounts of material/particles that would be expected to undergo increased degradation were observed. As such, based on the geological assessment and the UCS test results, it is anticipated that long-term degradation of the blast rock fill would be relatively minor low for this site.

5 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 corresponding to Day 113 and Day 115 (since the start of construction) for the SBL and NBL embankments, respectively. At the time of writing this paper, monitoring results taken up to April 16, 2019 were available corresponding to Day 800 since the start of construction and approximately 686 days (or about 1.9 years) following completion of filling.

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 on Figure 4. The data in this figure includes the displacements measured up to Day 800 by the seven settlement plates as well as at the point of maximum settlement along the SAA. The sequence of rock fill placement as depicted by the fill thickness versus time is also shown on the figure.

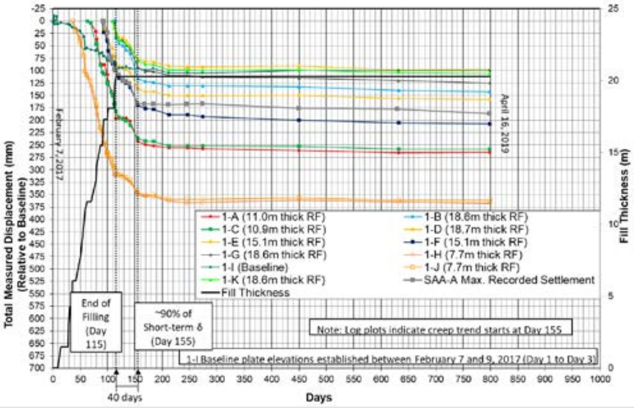

Figure 4. Area 1 – Total rock fill settlement and fill thickness versus time for SPs and SAA.

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 has been corrected to discount the foundation soil settlement and the net rock fill settlement has been plotted versus log-time in Figures 5, 6 and 7 for Areas 1, 2 and 3, respectively.

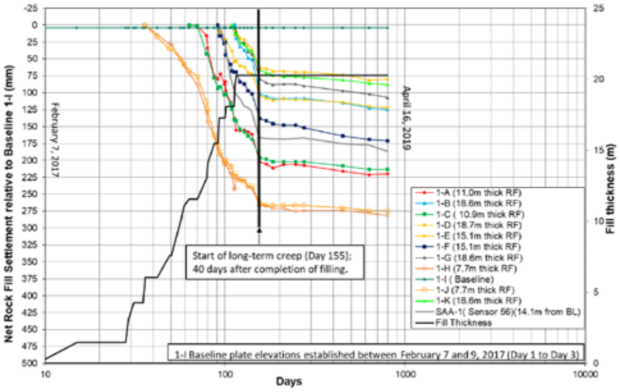

Figure 5. Area 1 – Net rock fill settlement versus log-time for SPs and SAA.

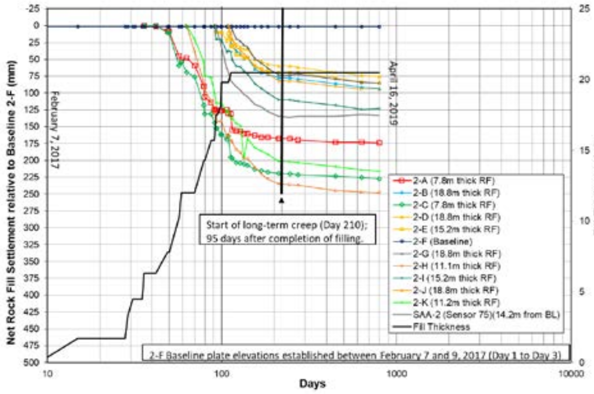

Figure 6. Area 2 – Net rock fill settlement versus log-time for SPs and SAA.

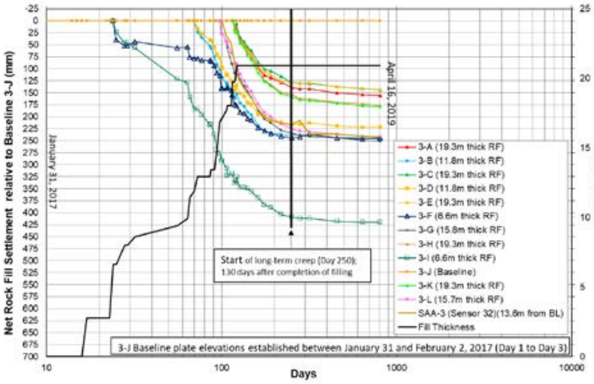

Figure 7. Area 3 – Net rock fill settlement versus log-time for SPs and SAA.

6 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 the settlements measured during construction, the settlement immediately after construction (or what is referred to herein as 'short-term'), and the long-term, post-construction (or creep) settlement trend.

6.1 Settlement During Construction

A detailed analysis of the settlement data collected during rock fill placement is presented in Varshoi et al. (2017). A re-explanation of the method of analysis will not be repeated herein, but a summary of the range and average normalized rock fill settlement calculated during construction for each of the monitoring areas is presented below in Table 3. It is noted that the settlement during construction was erroneously referred to as 'short-term' rock fill settlement in the 2017 paper when in fact it should have been denoted as the rock fill settlement during construction.

Table 3. Settlement During Construction - Rock Fill Embankment

Settlement Monitoring Area	Settlement During Fill Placement[1]		
	Min	Average	Max
Area 1	1.13% H	1.65% H	1.91% H
Area 2	0.62% H	1.13% H	1.60% H
Area 3	1.08% H	1.94% H	3.03% H

Note(s): 1. Settlement as a function of rock fill thickness (H).

The data indicates that for the rock type and embankment heights at this site, the settlement of compacted rock fill (Areas 1 and 2) that takes place during construction is on the order of about 1% to 2% of the total fill thickness and the settlement during construction of the uncompacted rock fill (Area 3) is more variable and on the order or about 1% to 3%. These results are of the same order of magnitude as those reported in literature by Farhangi et al. (2014).

For rock fill placed and compacted in accordance with OPSS.PROV 206 (Area 1), it appears that assuming settlements during construction equal to about 2%·H would be a conservative assumption. It is noted that this estimate of rock fill settlement would only apply to the quantity of fill requirement during construction. It would not impact the design in terms of the post-construction settlement performance of the roadway.

6.2 Short-Term Settlement

The short-term settlement was established based on the survey results of the SPs 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 on Figures 5, 6 and 7 (for Areas 1, 2 and 3, respectively), were used to establish 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 rest of the settlement versus time data was defined as the end of the short-term settlement period. With this 'Day' defined, both the duration of the short-term settlement period and the magnitude of the short-term settlement could be calculated. Table 4 summarizes the results of this interpretation.

Table 4. Short-Term Settlement - Rock Fill Embankment

Settlement Monitoring Area	Embankment Height (m)	Short-Term Settlement[1]		
		Min	Average	Max
Area 1	0 to 10	0.12% H	0.17% H	0.21% H
	10 to 20	0.28% H	0.34% H	0.45% H
Area 2	0 to 10	0.20% H	0.35% H	0.56% H
	10 to 20	0.20% H	0.30% H	0.35% H
Area 3	0 to 10	0.22% H	0.50% H	0.67% H
	10 to 20	0.56% H	0.77% H	1.06% H

Note(s): 1. 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 0.2% to 1.1% of the total rock fill thickness. It is not possible to compare these results to values previously reported in literature because it appears that this so-called 'short-term' settlement is typically ignored and it is only the settlement trend over the long-term trend that is generally reported, however these settlements are lower than the ones recommended in the MTO guideline (2010) for both compacted and end-dumped rock fill.

For rock fill placed and compacted in accordance with OPSS.PROV 206 (Area 1), it appears that assuming short-term settlements equal to 0.25%·H for fill heights up to 10 m, and 0.5%·H for fill heights up to 20 m%·H would be a conservative assumption. This is less than the amount recommended in the current MTO guideline (2010) for the evaluation of short-term settlement of compacted rock fill. The short-term settlements measured by settlement plates in each of the monitoring areas have been normalized as vertical strain for the rock fill embankment height and plotted on Figure 8, along with the short-term settlement recommendations in the current MTO guideline (2010) for comparison.

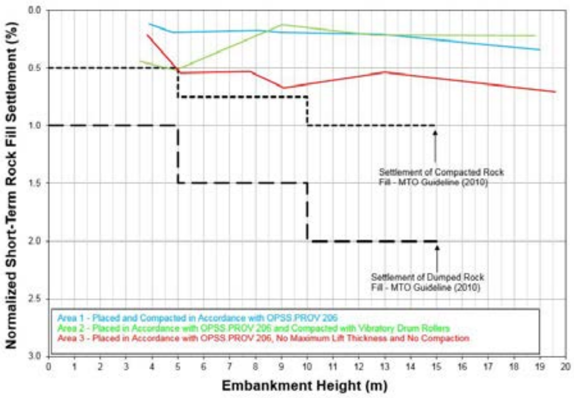

Figure 8. Normalized Short-Term Rock Fill Settlements vs. Embankment Height.

More importantly, the data indicates that this short-term settlement occurs relatively quickly and is finished within about 40 days following completion of filling (for compacted rock fill, Area 1) and is finished within about 130 days following completion of filling (for end-dumped rock fill, Area 3). This time frame for the duration of short-term settlements is less than that recommended in the current MTO guideline (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 the next section.

6.3 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 on Figures 5, 6 and 7. 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. 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 5 summarizes the results of this interpretation.

Table 5. Long-Term Rock Fill Settlement

Settlement Monitoring Area	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	0.18% H
Area 2	95 days	0.09% H	0.12% H	0.17% H
Area 3	130 days	0.14% H	0.16% H	0.18% H

Note(s): 1. Settlement as a function of rock fill thickness (H) per log-cycle of time.

The data indicates that for the rock type and embankment heights at this site, the settlement of rock fill that takes place in the long-term is on the order of about 0.1% to 0.2% of the total fill thickness per log-cycle of time based on the long-term data collected to date. These results are comparable to those summarized for long-term settlement of rock fill dams in the study that was carried out for the Ontario Ministry of Transportation and Communications (RR227, 1982). However, they are much larger than the conclusions in RR227 (1982) which states that for highway embankments up to 20 m in height, extrapolation of the data from the dams indicates that the long-term settlement would be 0.01% of the fill thickness (per log-cycle of time) for compacted rock fill and 0.07% of the fill thickness (per log-cycle of time) for end-dumped rock fill.

For rock fill placed and compacted in accordance with OPSS.PROV 206 (Area 1), it appears that assuming long-term settlements equal to about 0.15%·H per log-cycle of time would be a reasonable (average) assumption. For "end dumped" rock fill with heights up to about 20 m, it appears that assuming long-term settlements equal to about 0.20%·H would be a reasonable (average) assumption. This is comparable to/ slightly greater than the amount recommended in the current MTO guideline (2010) for the evaluation of long-term settlement of compacted rock fill. It should be noted that the long-term settlement (creep) occurs over log-cycles of time and as such, the design should take into account the total time frame over which the long-term (creep) settlement would occur. Given that for Area 1, the short-term settlement was completed in about 40 days following completion of filling, if we assume that the typical design life for a pavement structure is about 10 years (3,650 days), then approximately 2 log-cycles of time should be considered in the creep calculation for rock fill settlement. This approach would result in an overall larger magnitude of long-term creep settlement than what would be calculated using the current MTO guideline (2010) for the evaluation of long-term settlement of compacted rock fill.

7 DISCUSSION AND CONCLUSIONS

A review of the results of the settlement monitoring as presented in Sections 5 and 6 indicates the following conclusions.

- The results of this settlement monitoring program provide an in-depth understanding of settlement of highway fill embankments constructed of strong to very strong blast rock fill, in terms of during construction, short-term and long-term settlements magnitudes and the duration of short-term settlements.
- The magnitudes of settlements during construction may be used to determine the effectiveness of the compaction method. By comparing the settlements during construction measured in Areas 1 and 2 and supported by the findings in Farhangi et al. (2014), it can be concluded that a more effective compaction method will generate greater magnitudes of settlement during construction and provides a more consistent settlement behaviour after construction.
- The results of this study confirm that the placement and compaction method as specified in OPSS.PROV 206 yield acceptable settlement performance (consistency and magnitude of post-construction method).
- In Area 2, the settlement during construction was noted to be smaller than Area 1, which could be attributed by insufficient compaction due to the difficulties associated with compacting with a vibratory drum roller, as reported by the Contractor.
- Considering the site access limitations and the proximity of Area 3 to Areas 1 and 2 that precluded uncontrolled "end-dumping" of the rock fill in Area 3, the results of the settlement monitoring in Area 3 are not entirely applicable to a case where rock fill embankment is built by end dumping, such as the case of construction of rock fill dams, etc.
- In general, variability in rock fill settlement should be expected due to inherent variations in the rock fill embankment independent of the placement/compaction technique.
- The magnitudes of measured short-term settlements for all three areas are smaller than those recommended by the current MTO guideline (2010). It appears that assuming short-term settlements equal to 0.25%·H for fill heights up to 10 m and 0.5%·H for fill heights up to 20 m, placed and compacted in accordance with OPSS.PROV 206 and short-term settlements equal to 0.5%·H for fills heights up to 10 m and 1.0%·H for fills heights up to 20 m for "end dumped" rock fill would be an appropriate design assumption, which could be adopted in a future revision of the MTO guideline.
- The short-term settlements were noted to occur more quickly than the timeline suggested by the current MTO guideline (2010). It can be assumed that the short-term settlements occur in a period of 1.5 months after completion of construction for embankments constructed in accordance with OPSS.PROV 206 and 4 to 6 months after completion of construction for end dumped rock fills.
- Based on the settlement monitoring data collected to date, it appears that the magnitude of long-term settlements is independent of rock fill thickness for embankments up to 20 m high.
- The results of the long-term settlements indicate that extrapolating a trendline from data collected for rock fill dams, with heights greater than 40 m and up to 100 m, is not appropriate for predicting the long-term settlements (i.e., creep) of highway rock fill embankments due to differences in heights but also different construction and compaction techniques.
- It is noted that the long-term settlement results collected to date support the typical approach of calculating long-term (creep) settlement of rock fill embankments over log-cycles of time. The trend will be further verified by the results of the remainder of the settlement monitoring program.
- The settlement monitoring results, if collected after opening the highway to vehicular traffic, may be used to comment on any potential effects of traffic loading on the long-term settlement of rock fill embankments.
- Considering that the short-term rock fill settlement occurs relatively quick (less than 6 months and in the case of compacted rock fill less than 2 months), the long-term settlement value should consider the settlement that would occur over two log-cycles of time for design of typical highway embankments in Ontario assuming a typical 7 to 10 years of pavement maintenance recurrence.

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