Mitigation of Ongoing Road Settlement Using Lightweight Cellular Concrete – A Case History.

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ABSTRACT
The rideability on segments of a road built in Delta, British Columbia, has been affected by ongoing differential settlement due to the presence of organic and soft soils in the subgrade. Based on a detailed assessment of survey monitoring data collected over a period of 5 years, it was concluded that the rate of settlement observed was larger than that required to meet the specified rideability conditions. A trial section along the affected area was selected to evaluate the performance of a remediation option based on the use of lightweight cellular concrete (LCC). After construction was completed and the road opened to traffic, survey monitoring was conducted on this segment of the road for about 6 months. The survey information has shown maximum ground displacements in the order of 3-4 mm, which are considered within the expected design values.

RÉSUMÉ
La maniabilité sur des segments d'une route construite dans Delta, en Colombie-Britannique, a été affectée par le tassement continu en raison de la présence de sols organiques et mous sur le sous-sol. Sur la base de l'étude des données de surveillance de l'enquête recueillies sur une période de 5 ans, il a été conclu que le taux de tassement observé était supérieur à celui requis pour répondre aux conditions de maniabilité requises. Une section d'essai le long de la zone touchée a été sélectionnée pour évaluer les performances d'une option corrective basée sur l'utilisation de béton cellulaire léger (LCC). Une fois la construction terminée et la route ouverte à la circulation, un suivi d'enquête a été effectué sur ce segment de la route pendant environ 6 mois. Les informations d'enquête ont montré des déplacements de sol maximum de l'ordre de 3-4 mm, qui sont considérés dans les valeurs de conception attendues.

1 INTRODUCTION

Roads built on ground with sensitive organic materials in the subgrade are prone to uneven settlement due to the pavement structure and traffic loading. The road settlement, if not remediated, will likely contribute to unacceptable rideability conditions over time. A road in Delta, BC. has been the focus of study since 2016 due to the uneven settlement throughout three zones of the road. A monitoring plan using survey points was implemented at each zone to evaluate the settlement every six months. The findings from this evaluation indicated the increase of settlement with time due to the presence of highly compressible and organic soils in the subgrade. Due to the sensitivity of the subgrade materials to settlement, lightweight cellular concrete (LCC) has been considered as a viable construction option to avoid overloading the subgrade and improve long-term rideability. A trial section was constructed in July 2021 and is currently under periodical review.

2 BACKGROUND

In January 2016, MEG Consulting Ltd. (currently part of Tetra Tech Canada Inc.) was approached by the Concessionaire responsible for the operation and road maintenance of a highway segment located north of Delta, BC to evaluate ongoing road settlement. Three zones of this road were being affected by ongoing total and differential settlement, as observed in Figure 1. A monitoring plan was defined with the concessionaire to focus on the areas most severely affected, which are known to be built on top of compressible organic materials as part of an old landfill. Settlement monitoring points were defined at 5 to 10 m spacing along the fog lines, outside lane lines, middle lane lines, and the median for both directions of traffic. The first survey was taken in February 2016 with reference to top of pavement. A subsequent survey was taken in June 2016 for comparison, with successive monitoring surveys every 6 months. Gaps of data from the date in which the road was put into service (November 2013) to the beginning of the monitoring survey plan were accounted for using available LiDAR data collected in January 2014 and August 2015.

Figure 1. View of localized settlement observed on the road in Delta, BC.

Although the main assessment of the road was extended over three zones experiencing differential settlement, this study is focused on one of the zones, namely Zone 2, which had developed differential settlement and a localized hard point. Due to this localized issue, Zone 2 underwent maintainance repairs to improve the rideability starting in May/June 2015.

2.1 Geotechnical Conditions

The geotechnical conditions for the area of interest include a layer of soft to firm fibrous to amorphous peat and organic silt relatively close to the ground surface. The thickness of this organic layer varies from 2 to 4 m and is typically covered by 6 to 8 m of fill. A layer of clay (5 to 10 m thick) was observed below the organic material; however, the settlements have been attributed mainly to the organic layer closer to the surface. The groundwater level in the area is expected to be approximately 5 to 6 m below the road surface.

Based on the record drawings, this area was built on a transition of cut and fill, with maximum grade changes of about 4 m.

2.2 Construction Surcharging

Records from road construction indicate the use of preloading within the area of interest. The measured settlement across all preloads has an average rate of about 300 mm per log cycle of time in days after preload placement. Based on the records, it was concluded that primary consolidation was generally completed prior to removal of most preloads. It was also noted during this review that the measured settlements were larger than those estimated during the original design.

3 EVALUATION OF SETTLEMENT

LiDAR data was used to evaluate the settlement rate before commencing the monitoring survey plan. The difference in elevations from January 2014 to August 2015 (19 months) indicated that settlements ranging from 50 to 290 mm had occurred in Zone 2. The first assessment of the settlement data included the evaluation of the survey data over a 4-month period, from February 2016 to June 2016. Based on the observed trends during this first evaluation, the settlement rates appeared to be consistent over this period, suggesting that the area of interest was likely undergoing secondary settlement. It was agreed at this point that the ongoing settlement would likely increase the differential settlement over time.

On a subsequent review, with data up to September 2017, the survey data was used to estimate the settlement. Considering that secondary settlement occurs on a logarithmic time scale, part of the assessment entailed selecting an appropriate date for end of primary consolidation for the analysis. Based on the surcharge records, it was estimated conservatively that primary consolidation was completed by January 2013, which was taken as the date of surcharge removal throughout the site. The settlement rates were used to estimate the potential settlement by the end of a 5-year period (2022) and by the end of concession of the road (2034). Based on the evaluation it was indicated at the time that pavement profiling was an appropriate short-term solution for maintenance of the road, provided that the operation resulted mainly in cut of the pavement, with fills limited to 100 mm to avoid reloading. Any reprofiling operation would have to be followed by a monitoring survey to assess the effects of such an intervention on the settlement rate. The ground survey was discontinued after September 2017 and restarted in June 2019, followed by regular survey campaigns every 6 months for further analysis.

A few interventions were completed on Zone 2, which were reflected in the survey data. The first was a milling and pavement reconstruction conducted in May/June 2015, prior to the August 2015 LiDAR data collection. The second was another milling/paving in May 2017 to smoothen high points. Milling operations to smoothen high points in Zone 2 were subsequently carried out in November 2018 and September 2019. Details of the road surface after this last operation are observed in Figure 2.

Figure 2. Detail of milled pavement along Zone 2.

In January 2020, the mean settlement rates between February 2016 and December 2019 were used to estimate possible short-term and long-term remediation measures. For this, the rate of settlement was evaluated at the location of maximum deformation within the area of interest. The logarithmic rate of settlement remained practically constant from February 2016 to December 2019, except for a small decrease in the rate observed at Zone 2, likely a result of the interventions carried out at this location. The rates of settlement for Zone 2 are presented on Figure 3 for reference. Based on the settlement rates observed up to December 2019, the road was expected to settle another 300 to 400 mm by the end of the concession period (2034) in Zone 2.

Local maintenance measures taken at Zone 2 involved the milling and infill of pavement at high points, however, it was noted that local settlement increases had occurred on other areas of the road where fill thicknesses of up to 175 mm have been added during remediation works. Therefore, local additions of fill in excess of 50 mm would

have to be avoided during the evaluation of remediation measures for this road.

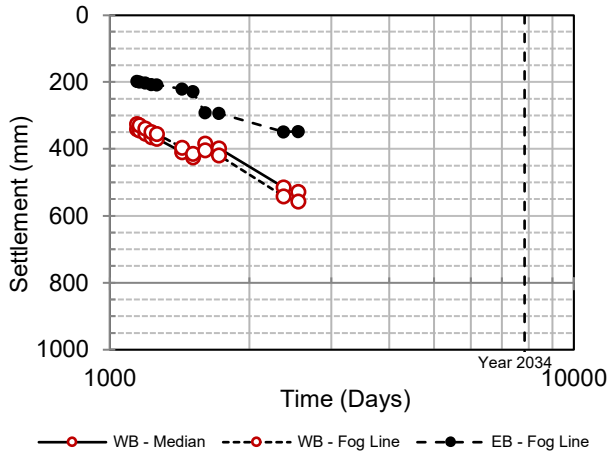

Figure 3. Settlement at locations of maximum deformation along Zone 2 (February 2016 to December 2019).

4 REMEDIATION MEASURES

Three remediation measures were evaluated to improve the short- and long-term rideability conditions, long-term being to the end of concession period (year 2034). Based on the review of the settlement data up to December 2019, these remediation measures had to align with the following premises:

- The maximum additional loading should be limited to the equivalent of no more than 50 mm of fill.
- If the road is required to be raised and the addition of fill is more than 50 mm thick, the material should be replaced with lightweight fill.
- If lightweight fill is used, the maximum pressure on top of the compressible layer should reach a net-zero load condition to avoid additional effects on the observed secondary settlement rate.
- The addition of lightweight fill is bounded in some areas of Zone 2 by a landfill liner cap that is placed on top of the compressible layers. Any excavation should be limited to leave at least about 0.3 m of fill on top of the liner to avoid detrimental effects on the liner.

4.1 Road Surface Reprofiling

The first remediation scheme considered reprofiling the current pavement to a smooth profile to improve the rideability of the road, either by filling the sags, or cutting the high points of the road profile. Applying this option for Zone 2 would potentially resolve the differential settlements in the short term, but the rideability criteria by the end of concession period would not be met. Moreover, the history of settlement in this area showed that there was a local differential settlement condition developing due to a hard point, which had been milled on several occasions in the past. This condition would likely develop again before the end of concession period under this scenario.

4.2 Road Surface Reprofiling and Fill Compensation Using EPS

The second remediation scheme considered attempts to improve the road profile by raising the road and replacing the additional required fill thickness with blocks of expanded polystyrene (EPS) in areas where major intervention of the pavement structure is economically feasible. The EPS would need a minimum fill cover on top to protect the EPS from damage, and to control buoyancy due to the design flood events. Based on the assessment of this option, deep excavations were required to satisfy the load compensation and buoyancy criteria, but the presence of the landfill cap liner was limiting the depth of these excavations at some locations. Considering that the rate of settlement may remain the same after the intervention, the analysis indicated the rideability conditions by the end of the concession period would deteriorate and likely be unacceptable by 2034. In addition, a concrete slab might be required on top of the EPS fill to control potential local differential settlements.

4.3 Road Surface Reprofiling and Compensation Using LCC

Tetra Tech considered the use of lightweight cellular concrete (LCC) as a third option for remediation of the road. LCC is a mix of Portland cement with water and a foaming agent that when mixed with compressed air generates a flowable foam. When this fill cures with entrapped air bubbles, the material has a wet (cast-in-place) density typically lower than 800 kg/m^3, with compressive strength up to 1.1 MPa (ACI523.1R-06, 2006).

In Canada, LCC has been used satisfactorily in roads with compressible soils in the subgrade. Such applications include the study presented by Dolton et al. (2017) for a section of Dixie Road in the region of Peel, Ontario. The road was undergoing differential settlement due to a layer of peat in the subgrade, and LCC was used in the pavement structure to avoid extensive excavation below the groundwater level to remove the peat. Construction occurred in 2009, and by 2016 no settlement-related issues were observed (Dolton et al. 2017). Similar applications have been implemented in Edmonton, AB (Donovan et al. 2018), Calgary, AB (Dolton and McIntosh 2018) and Victoria, BC (Dolton et al. 2016), where the LCC has been included into the pavement structure and settlement-related issued have not been observed within 8 to 18 years following reconstruction.

Based on these case histories, the use of LCC was considered to allow the net-zero loading condition without requiring large excavation depths. Also, the cases referenced seem to indicate that the addition of LCC should control the localized differential settlement occurring in the subgrade and would dissipate its effects on the road surface. Considering these precedents, LCC was

considered as a viable option to remediate the localized settlement issues observed at the area of interest.

5 TRIAL SECTION – CONSTRUCTION OF ZONE 2

Considering that Zone 2 was undergoing a localized differential settlement at the time of the study (2020), the use of LCC as the remediation option was favored over the other options for the intervention in this zone. To set a precedent for the use of LCC on this road, it was advised to use Zone 2 as a trial section due to the limited extension of the zone for the intervention and depth of excavation required.

5.1 Design

To reach a desirable road surface along Zone 2, the pavement was proposed to be raised at the locations that had undergone the most settlement, for a total length of intervention of about 115 m. The geotechnical design required the evaluation of the loading conditions at the subgrade for the locations requiring fill replacement with LCC. Under the limitations presented in Section 4, any location that required more than 50 mm of fill would have LCC under the pavement to reach a net-zero loading condition. In the design, an additional 5 to 10 kPa unloading of the subgrade was considered as a buffer to account for future maintenance works. For estimating the required thickness of LCC at each location, a unit weight of 475 kg/m^3 and a minimum compressive strength of 0.4 MPa after 28 days of curing were assumed. The minimum thickness of LCC required for this design was estimated to be 0.5 m.

The pavement structure designs were based on an estimated composite subgrade resilient modulus (M_R), where the top of the subgrade is influenced by a minimum thickness of LCC on top of a prepared subgrade. Based on technical specifications provided by the LCC supplier (CEMATRIX), the LCC with cast-in density of 400 to 500 kg/m3 is expected to have an M_R of about 400 to 550 MPa, respectively. An M_R of 35 MPa was assumed for the prepared subgrade based on Falling Weight Deflectometer (FWD) testing previously completed along Zone 2. The design pavement thickness varied between 290 and 310 mm of asphalt on top of minimum 150 mm of Well-Graded Base (WGB, 25 mm minus grading).

Considering that the longitudinal slope of the road was in the order of 2.3% (horizontal to vertical, H:V), the LCC had to be placed in steps to accommodate such grade change. The steps in this design allowed for a minimum thickness of 150 mm granular base between the asphalt layer and the LCC. The thickness of LCC under this scheme varied from 500 to 800 mm at each step.

Based on the proximity of the landfill cap liner to the bottom of excavation at several locations in Zone 2 (within 0.5 m below the bottom of excavation), the addition of a layer of geotextile at the bottom of the LCC base was considered in the design to avoid migration of the pour below the excavation limits. Additionally, a biaxial geogrid was included at the bottom of the LCC (over the geotextile) to improve the LCC performance during settlement of the subgrade.

5.2 Construction

The construction went underway during July 2021. Once the excavation depth was reached, geotextile (Nilex 4545) berms were placed to divide the steps for the LCC placement and to avoid flow of slurry from one section to another. The biaxial geogrid (Terrafix TBX12 was also placed before the first lift of LCC slurry. The LCC was prepared at site using a dry mix procedure, where the cement and water were combined into a slurry and then mixed with the foaming agent at the site in a batch plant. The mix was later pumped into the sections in two stages of no more than 600 mm thick, over two days. A total of 1240 m^3 of LCC were poured during construction. Stages of the construction process are shown on Figures 4 to 6.

Figure 4. Exposed pavement layer on the eastbound median during excavation of the westbound section.

Figure 5. Detail of geotextile/geogrid placement and separation of steps for pouring of LCC.

Figure 6. Pouring of LCC between geotextile berms.

During construction, catch basin pipes were encountered within the depth of the excavation and had to be removed. Before pouring LCC, these pipes were placed at their respective locations and tied to the bottom of excavation with rebar and steel wire to avoid floatation of the pipes while pouring LCC, as observed on Figure 7. The pipes were embedded within the LCC layer, as they can be daylighted in the future, if required.

Figure 7. Catch basin lead during pouring of LCC.

The landfill cap liner was expected to be very close to the bottom of the excavation toward the east end of the Eastbound lanes. During the excavation of these lanes the liner was detected within 50 mm of the proposed base of LCC. To comply with the change in grade in the longitudinal direction, one of the proposed geotextile berms in this section had to be eliminated to avoid damaging the liner with the rebars holding the berm. Instead, the LCC was poured in two stages with a 1% surface slope so that the final grade was met with a final surface slope of near 2%. By implementing this change, the thickness of LCC achieved in this section was sufficient, without risking the integrity of the liner or the minimum thickness of the pavement structure above the LCC.

The WGB granular base was placed the day after the final lift of LCC was poured (Figure 8), to allow for curing of the slurry. The base gravel was placed in lifts and was compacted using static methods at locations where the gravel thickness on top of LCC was less than 350 mm, based on recommendations from the LCC supplier. After the first 350 mm were compacted, vibratory methods were used to compact the base gravel until reaching the design elevation at the bottom of asphalt. At locations where the total granular base thickness above the LCC was less than 250 mm, the asphalt base lift was compacted using static methods. The placement of asphalt commenced two days after the final LCC lift was poured.

Figure 8. WBG granular base placement on cured LCC.

Throughout the operation, quality control of the LCC was conducted continuously by measuring the as-cast density of the batch and collecting cylinders for further testing of the compressive strength. Cast-in-place density ranged from 445 to 470 kg/m^3 and compressive strength at 28 days ranged from 0.6 to 1 MPa.

The construction was performed over the lanes of one direction of traffic at the time. The operation generally commenced on Friday evenings and was completed by the following Thursday morning. Overall, it took a period of two weeks to complete the construction for Zone 2.

6 ROADWAY PERFORMANCE

Following the major intervention of Zone 2, a survey was performed in September 2021 to record the new road surface using the same reference locations and intervals as established in the first survey in February 2016. This survey data was considered as the new baseline of the road surface for Zone 2.

Another survey was performed in December 2021 as part of the periodical monitoring survey along this road to keep track of total and differential settlements occurring along the repaired segment. When comparing the road profile from December 2021 with the new baseline in September 2021, the total settlements observed over the

period of 92 days were in the order of 1 to 4 mm. This amount of movement is within the range of error of the survey equipment, therefore, the movement occurring at Zone 2 is considered negligible during this period. Monitoring survey data will continue to be gathered in periods of six months at Zone 2 to evaluate the performance of this remediation.

7 CONCLUSIONS

A trial section of a road in Delta, BC was selected to undergo a major intervention with the use of LCC to control total and differential settlements due to highly compressible materials in the subgrade. The survey data collected after the intervention indicated total ground settlements in the order of 1 to 4 mm between September 2021 to December 2021. These settlements are within the range of error for the survey equipment, therefore, the ground movement within Zone 2 is considered negligible up to 6 months after the intervention. Moreover, due to the positive outcome in the application of LCC in Zone 2, this remediation method is being considered as a preferred option for other locations affected with similar challenges due to differential settlements on highly compressible subgrade.

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