

- reduced post-construction settlements of the foundation;
- potential reduced delay in construction; and
- no requirement for stabilizing toe berms.

The disadvantages of this option are:

- generation of large volume of excavation spoil requiring disposal/management;
- increased post-construction settlement of rock fill, typically requiring a preload period, in addition to sub-excavation, to satisfy the settlement performance criterion;
- potential for requiring a larger right-of-way corridor due to backslope requirements;
- potential need for temporary excavation support where an embankment widening is constructed adjacent to existing highway embankments, and
- requires greater quantities of rock fill.

6.4.6 Ground Improvement

Ground improvement techniques (such as rammed aggregate piers or deep soil mixing) could also be considered to improve the performance of the subsoils. Rammed aggregate piers are not considered practical at this site due to the relatively great depth required to extend the columns to an appropriate bearing layer and due to the lack of lateral confinement that can be provided by the soft consistency of the cohesive deposits. Deep soil mixing, however, may be technically feasible but would require an in situ trial section to be constructed followed by completion of the soil mix design for the entire embankment.

Deep soil mixing involves the in-situ mechanical blending of soil columns with a binder material in a grid pattern under the full width and length of the affected embankment to improve the engineering properties (compressive strength, shear strength and/or permeability) of the soil layer(s). The binder material typically consists of a cement-based grout slurry (wet soil mixing) or a cement-slag powder (dry soil mixing). For wet soils (i.e., moisture contents greater than about 60 per cent), dry soil mixing is generally more cost effective than wet soil mixing due to the costs associated with supplying of grout and mixing it adequately into the soil.

The strength of the improved soil ("soilcrete") develops differently with time depending on the type of soil and the amount and type of binder material, but generally increases with increasing binder dosage. The strength improvements are generally highest for inorganic soils with moderate water contents. Organic soils and peat soil mixtures, as encountered in the near surface cohesive deposits of the high fill/swamp areas, can be stabilized with a binder material but information on the adequacy or practicality of increasing the strength and stiffness of the soils is not readily available.

The "soilcrete" column type, size and spacing would have to be designed by a specialist ground improvement contractor. The amount of binder material required in each column to provide adequate increase in the stiffness of the soil mass is not possible to estimate without bench scale testing and may possibly require a field test program. However, in general, the higher the water content and lower the strength of the existing soils, the larger the amount of binder material that is required and the closer the required spacing of columns will result in a sufficient level of improvement.



The high cost of mobilization of equipment and materials, the use of specialized equipment and potential large volume of mixing additive required for the extent of the soil improvement area may offset the cost savings associated with reduced sub-excavation and soil disposal.

The advantages of the deep soil mixing option are:

- improved stability;
- reduced post-construction settlements of the foundation; and
- reduced sub-excavation and soil disposal quantity.

The disadvantages of the deep soil mixing option are:

- specialized testing and design required;
- specialized construction equipment and supplies required;
- additional time for soil mixing required prior to embankment construction; and
- risk that strength gains may not be cost effective and/or more conventional mitigation measures may still be required.

6.4.7 Instrumentation and Monitoring

For some areas where the preloading and surcharging options are adopted and in all areas where staged construction and/or wick drains foundation options are adopted, the magnitude and time-rate of settlement as well as dissipation of pore pressures during and after construction of the embankments should be assessed with monitoring instrumentation. Such monitoring would consist of installing settlement pins/stakes (Ss), settlement plates (SPs) and vibrating wire piezometers (VWPs) below the embankments and taking regular measurements/readings at given intervals of time during and after construction of the embankments for the duration of the preloading/surcharging period. In addition, standpipe piezometers (SPPs) may be required and are usually installed to provide background pore pressure readings for the vibrating wire piezometers. This monitoring instrumentation is particularly important where it is considered necessary to carefully monitor the stability of the foundation soils during staged placement of embankment fill.

The extent of instrumentation and the frequency of monitoring required will depend on the foundation treatment alternative chosen for a given site and the height of the proposed embankment fill. Specifications for the type, number and layout of the instrumentation, together with the supply, installation, protection and monitoring frequency and action levels should be included as a NSSP in the Contract Documents.

6.5 Results of Analysis

The results of the stability and settlement analyses for each high fill/swamp crossing area are provided in the following sections. In addition, the options and recommendations for achieving the target FoS for the required embankment geometry and for minimizing the time-dependent, post-construction settlements are also discussed. For high fill/swamp crossing areas H1, H2 and H3 that require stability and/or settlement mitigation, the advantages, disadvantages, relative costs, and risks/consequences of various alternatives for these areas

are summarized and ranked in the Evaluation of Stability/Settlement Mitigation Options Tables A1, B1, B2 and C1 in the respective Appendices.

In areas where the embankments are being widened and the overall grade raise is limited, it is anticipated that there will not be any significant risk of instability of the embankments. In these areas there is typically no need to implement any special construction procedures or schedule to maintain stability or to mitigate differential settlement of the foundation soils.

In areas where the foundation soils are comprised of cohesive deposits and the presence of weak/soft cohesive deposits constitutes zones of potential instability for the proposed embankments, time-dependent settlements of the new embankments are expected. In these areas, consideration must be given to an enhanced design and/or to follow a construction sequence that will achieve the minimum target FoS of 1.3 for the proposed new embankment height and geometry and limit the post-construction settlements and subsequent maintenance of the new highway pavement structure.

For new embankments constructed with rock fill or where sub-excavation and backfilling with rock fill is carried out, settlement of the embankment rock fill is also expected due to compression of the rock fill itself (see Section 6.2.3.3). In these areas, the post-construction settlement of rock fill may exceed the settlement performance criterion. As such, the embankment would need to be preloaded to obtain acceptable post-construction settlements associated with long-term performance.

6.5.1 Highway 17 – STA 12+220 to 12+570 High Fill H1

Along this section of the alignment, the proposed WBL will be a widening of the existing Highway 17 embankment while the proposed EBL will be constructed over the native low-lying swampy ground to the south of the existing highway and proposed widening. Therefore, the EBL and the WBL embankments in this high fill/swamp area will be considered separately in Sections 6.5.1.1 and 6.5.1.2, respectively.

6.5.1.1 Highway 17 WBL – STA 12+220 to 12+570 High Fill H1

Generally, the proposed Highway 17 WBL embankment will be constructed essentially at the same location as the existing Highway 17 embankment between STA 12+220 and 12+570. The proposed WBL centreline will be slightly shifted to the south from the existing Highway 17 centreline resulting in embankment widening up to about 9 m and a grade raise up to 0.8 m at the south edge of pavement, particularly towards the eastern portion of this section. The existing embankment is up to about 5 m high above the surrounding swamp area although greater than 5 m of fill was encountered in some boreholes, suggesting that some peat was removed and/or settlement has occurred over time since embankment construction.

The subsurface soils along the proposed WBL alignment in High Fill Area H1 consists of embankment fill or a peat/topsoil deposit underlain by a sand and silt deposit and a cohesive deposit of varved, silty clay to clay transitioning into clayey silt, which in turn is underlain by deposits of silt, sand and silt to sand and sand and gravel to gravelly sand. The cohesive deposit is up to about 8 m thick in some locations and extends to depths up to 13.4 m below ground surface. Resistance to dynamic cone penetration and borehole advancement was



encountered at depths of up to 19.4 m below ground surface. Details of the subsurface conditions for this swamp crossing area are presented in Section 4.3 and shown on Drawings A1 to A3 in Appendix A.

The simplified stratigraphy and the associated unit weight, strength, deformation and time-rate consolidation parameters employed for the different soil types encountered in this area are summarized in Table 3. Additional details of foundation engineering parameters employed for the cohesive deposits (i.e., clayey silt/silty clay/clay) encountered in H1 are provided on Figure A21 in Appendix A. The piezometric condition used in the analyses assumes the water table is at the interface between the native and fill materials (at about Elevation 241.2 m).

The critical section for this area is located at about STA 12+400 along the proposed Hwy 17 WBL alignment and corresponds to the thickest cohesive deposit up to 7.9 m. At the critical section, the embankment widening is approximately 8 m and the grade raise at the south edge of pavement is approximately 0.5 m. The widening at the critical section creates a loading equivalent to about a 4.6 m above the existing ground at the toe of slope. Sub-excavation of peat at the toe of slope of up to 1.1 m is required, resulting in a total fill thickness of 5.7 m in the widened area.

6.5.1.1.1 Stability

The stability analyses carried out at the critical section indicates that the south side of the existing embankment has a Factor of Safety (FoS) less than 1.3 for a deep-seated, global failure surface that would impact the operation of the highway. The stability analyses carried out at the critical section after completion of construction (which includes the removal and replacement of the organic deposit and the construction of the WBL widening and Hwy 17 EBL embankment), indicates that the embankment will have a Factor of Safety (FoS) greater than 1.3 for a deep-seated, global failure surface that would impact the operation of the highway. Therefore, stability mitigation is not required for the WBL embankment in the High Fill Area H1, as shown on Figure A22.

6.5.1.1.2 Settlement

To estimate the magnitude of the expected settlements due to new construction, analysis was carried out at the critical section representative of the subsurface conditions within the high fill area, at approximately STA 12+400. Based on the results of the settlement analysis for the embankment widening, the short-term settlement of the foundation soils is estimated to be about 80 mm at the south edge of pavement. This estimated settlement in the Highway 17 WBL is comprised of about 10 mm of immediate settlement due to compression of the cohesionless deposits and about 70 mm of primary consolidation of the 7.9 m thick cohesive deposit.

Based on an average coefficient of consolidation (c_v) of about $2.0 \times 10^{-3} \text{ cm}^2/\text{s}$ estimated for the cohesive deposit in the normally consolidated range, the imposed loading conditions for the approximately 5.7 m of rock fill for the widening at the toe of slope and assuming two-way drainage of the 7.9 m thick cohesive deposit, it is estimated that about 90 per cent of the primary consolidation settlement will be completed in about 3 years.

The magnitude of secondary consolidation (creep) settlement for the normally consolidated portion of the cohesive deposit is expected to be about 55 mm per log-cycle of time for this area corresponding to about 50 mm over a 20-year period following completion of construction.

Although it has been assumed that rock fill would be utilized for the embankment widening, the raise across the existing embankment would be up to about 0.5 m and would be constructed of granular fill, which properly placed and compacted would have nominal settlement.

Since the total post-construction settlement, estimated to be about 120 mm at the south edge of pavement (comprised of 70 mm primary consolidation and 50 mm of creep) exceeds the settlement criterion of 50 mm (for an embankment a widening), settlement mitigation measures are required for the Highway 17 WBL embankment in the High Fill Area H1. Further, differential settlement of 60 mm between the new centreline and new south edge of pavement (assumed to be the edge of the travelled lane for this analysis) also exceeds the criteria of 200:1. It should be noted that higher magnitudes of total and differential settlement will occur beyond the south edge of pavement along the median slope.

6.5.1.1.3 Mitigation of Time Dependent Settlements

The presence of the up to 7.9 m thick silty clay to clay deposit influences both the stability and the settlement of the widened embankment for the proposed WBL. In order to minimize post-construction settlements, the alternatives presented below can be considered. The alternatives described have been evaluated and ranked on the basis of the advantages, disadvantages, relative costs and risk/consequences and are summarised in Table A1 in Appendix A. A summary of the settlement results for each alternative is provided in Table 4.

Given the presence of the 7.9 m thick cohesive deposit and the associated magnitude of primary and secondary consolidation settlement (about 120 mm) of the foundation soils under the south edge of pavement (i.e., approximately 0.5 m additional fill above the existing ground surface) and 60 mm of differential settlement between the new centreline and new south edge of pavement, the most practical method of construction is to preload the embankment allowing settlement to occur while the traffic is using the highway, followed by maintenance of the roadway in the future. This method does not meet the MTO settlement criteria for post-construction settlement but is more practical from a cost and a construction standpoint compared to other technically feasible options.

6.5.1.1.3.1 Consolidation and Maintenance

We recommend a construction approach that involves constructing the embankment to its final height, utilizing the embankment as a travelled highway and then conducting ongoing maintenance, as may be required, as approximately 90 per cent of the primary consolidation settlement is expected to be complete in about 3 years. This construction option does not meet the MTO settlement criteria; however, this alternative is the most practical option given the magnitude of total settlement at the new outside edge of the WBL north travelled lane which is about 120 mm (70 mm primary and 50 mm creep). Provided the peat is sub-excavated under the widened portion of the embankment in accordance with OPSD 203.020 (Embankments over Swamp, Existing Slope Excavated to 1H:1V) and the EBL embankment is constructed at the same time, the widened WBL embankment will remain stable while in use, however, the expected post constructed settlements may require maintenance. This alternative relies on the fact that while the expected settlements exceed the MTO settlement criteria for a widened embankment (Figure 3, MTO 2010), the embankment can still function as a travelled lane while consolidation takes place.

This construction approach may require the installation of instrumentation to monitor for settlement, however it is not required to monitor pore pressures for embankment stability. The embankment monitoring can consist of a

series of settlement plates installed in the embankment at the crest of the widened portion of the embankment provided guide rail installation is not impacted and the monitoring points remain accessible. Settlement plates in the shoulder or on the slope (or nail pins in pavement) will be required to be installed along the full length of the high fill section on the south side of the widened embankment at offsets to be determined once the final cross sections are known. For a 350 m long section, settlement plates at approximately 50 m spacing would be appropriate. At two stations, an array of settlement plates should be installed to monitor the cross-sectional settlement across the embankment widening. Monthly readings of settlement plates are recommended for the first year of monitoring and bi-monthly readings afterwards until the decrease in the rate of settlement indicates that the remaining settlement is within the MTO criteria, likely up to 3 years.

The total post-construction settlement (i.e., after construction of the widened embankment is complete and traffic is using the lanes) for the Highway 17 WBL embankment expected during the consolidation period is estimated to be 120 mm which exceeds the settlement criteria. The differential settlement of 60 mm between the new centreline and new south edge of pavement also exceeds the settlement criterion. During an approximately two year consolidation period, approximately 65 mm of settlement will have occurred at the new south edge of pavement and approximately 10 mm at the north edge of pavement. The estimated total and differential settlement after approximately 3 years of consolidation is about 55 mm and 50 mm at the new south and north edge of pavement, respectively, and a differential settlement of 5 mm, which meet the MTO criteria. The results of this analysis are shown on Figure A23.

The main advantages of this option are that there is neither a delay in the construction schedule nor any need to divert traffic for multiple years during staged construction. The disadvantages of this option are that it does not meet the MTO settlement criteria and future highway maintenance is likely to be required.

6.5.1.1.3.2 Lightweight Fill

In order to meet the settlement criteria without preloading, lightweight (EPS) fill could be incorporated into the widened embankment mass. The Highway 17 WBL embankment can be widened to the south using a 1 m thick layer of EPS under the pavement structure of the new embankment (full width, not to interfere with guide rail installation) and an additional 1.5 m of EPS (for a total of 2.5 m) would be required within the remainder of the south half of the new embankment. This will required sub-excavation of the existing fill to accommodate the EPS. The EPS should be stepped in 0.3 m to 0.5 m increments across the embankment and in the taper zones longitudinally along the highway. Essentially, with this quantity of EPS, the induced settlement will be minimal and will not result in the induction of creep settlement. Total and differential post-construction settlement is estimated to be less than 10 mm.

The main advantages of this option are that it meets the post-construction settlement criteria as well there is a no delay in the construction schedule. The disadvantage of this option is the substantial cost of EPS fill, which is typically an order of magnitude higher than other fill materials as well as having to excavate a portion of the existing embankments in order to install the EPS.

6.5.1.1.3.3 Full Sub-Excavation

The option of full sub-excavation of the cohesive deposit up to 8 m thick and up to 13.4 m below the road surface or up to 10.4 m below the ground surface at the toe of slope is not considered practical. To fully remove this deposit below the widened portion of the embankment, extensive shoring would be required along the full

350 m length of this high fill section. Further, preloading of the widened embankment would still be required due to the compression of rock fill, otherwise maintenance would need to be carried out at a later date based on the results of a monitoring program as described in Section 6.5.1.1.3.1.

6.5.1.2 Highway 17 EBL – STA 12+220 to 12+570 High Fill H1

Between STA 12+220 and 12+570, the Highway 17 EBL embankment will require a fill embankment up to 5.7 m high above the existing ground surface to achieve the vertical highway profile. The alignment extends across a low-lying swampy area. The subsurface soils along the EBL alignment consist of a surficial layer of peat/topsoil underlain by a sandy silt deposit and a cohesive deposit of clayey silt to silt transitioning into varved, silty clay to clay transitioning back into clayey silt, which in turn is underlain by deposits of silt to sandy silt, sand and silt to sand and gravelly sand. The cohesive deposit is up to 9.4 m thick in some locations and extends to depths up to 10.4 m below ground surface. Resistance to dynamic cone penetration and borehole advancement was encountered at depths of up to about 20.7 m below ground surface. Details of the subsurface conditions at this embankment are presented in Section 4.4, and are shown on Drawings A1 to A4 in Appendix A.

The simplified stratigraphy and the associated unit weight, strength, deformation and time-rate consolidation parameters employed for the different soil types encountered in this area are summarized in Table 3. Additional details of foundation engineering parameters employed for the cohesive deposits (i.e., clayey silt/silty clay/clay) encountered in H1 are provided on Figure A21 in Appendix A. The piezometric condition used in the analyses is the water table at the ground surface (about Elevation 241.2 m).

Although the existing highway embankment was not constructed with the incorporation of toe berms, it is unknown what other construction methods were used (i.e., staged construction, surcharging, etc.) to mitigate both settlement and stability. Further, the analysis of the existing embankment configuration (at the critical section at STA 12+320) indicates that for the shear strength design line considered applicable as shown on Figure A21, a Factor of Safety of about 1.1 is obtained. This implies that the existing embankment is stable, albeit with a Factor of Safety less than the current target of 1.3. It is also not known if there has been any long-term settlement that has occurred over the years and what maintenance has been carried out. It should be noted that the silty clay to clay deposit contains an approximately 1.5 m thick crust of higher shear strength, however, the design line interpreted from the undrained shear strength data does not reflect the crust due to the potential for disturbance, fissures, etc. that may be present within the crust.

The critical section (i.e., the greatest embankment height and maximum thickness of soft, compressible foundation soils) for this area is located at about STA 12+320 along the proposed Hwy 17 alignment. The proposed embankment is about 5.7 m high and the cohesive deposit is up to about 9.4 m thick.

6.5.1.2.1 Stability

The stability analyses carried out at the critical section indicates that after completion of construction (including removal and replacement of the organic deposit), the embankment will have a Factor of Safety (FoS) of less than 1.3 for a deep-seated, global failure surface that would impact the operation of the highway. Therefore, stability mitigation is required in the EBL for this High Fill Area H1.

6.5.1.2.2 Settlement

Based on the results of the settlement analysis at the critical section, for the condition where the organic deposits are removed and replaced with rock fill, the short-term settlement of the foundation soils is estimated to be about 770 mm. This estimated settlement in the Highway 17 EBL is comprised of about 110 mm of immediate settlement due to compression of the cohesionless deposits and about 585 mm of primary consolidation of the 9.4 m thick cohesive deposit.

Based on an average coefficient of consolidation (c_v) of about $2.0 \times 10^{-3} \text{ cm}^2/\text{s}$ estimated for the cohesive deposit, the imposed loading conditions for the approximately 5.7 m high rock fill embankment and assuming two-way drainage of the 9.4 m thick cohesive deposit, it is estimated that about 90 per cent of the primary consolidation settlement will be completed in about 3 years.

The magnitude of secondary consolidation (creep) settlement for the cohesive deposit is expected to be about 85 mm per log-cycle of time for this area corresponding to about 75 mm over a 20-year period following completion of construction.

In addition, the total settlement of the rock fill embankment itself (based on a 5.7 m high embankment at the critical section plus 0.8 m of removal of peat and replacement with rock fill) is estimated to be about 60 mm, with about 50 mm expected to occur within six months of construction of the embankment, 5 mm occurring during the next six months and about 5 mm expected to occur over the remaining design life of the embankment.

Since the total post-construction settlement (primary, creep and rock fill) exceeds the settlement criterion of 100 mm, settlement mitigation measures are required for the EBL embankment in High Fill Area H1.

6.5.1.2.3 Mitigation of Stability Issues and/or Time Dependent Settlement

The presence of the up to 9.4 m thick cohesive deposit influences both the stability and the settlement of the up to 5.7 m high embankment. In order to construct the embankments to achieve a FoS greater than or equal to 1.3, and to minimize post-construction settlements, the alternatives presented below can be considered. The alternatives described have been evaluated and ranked on the basis of the advantages, disadvantages, relative costs and risk/consequences and are summarised in Table A2 in Appendix A. A summary of the settlement results for each alternative is provided in Table 4.

Given the thick cohesive deposit (the bottom of which is up to about 10.4 m below ground surface) and the associated magnitude of primary and secondary consolidation settlement (about 660 mm) of the foundation soils under an up to 5.7 m high embankment, surcharging with wick drains and incorporating toe berms along the embankments into a staged construction schedule is considered the preferred mitigation alternative.

6.5.1.2.3.1 Surcharging, Wick Drains and Staged Construction with Toe Berms

We recommend a staged construction approach that incorporates wick drains into the cohesive stratum and a toe berm onto the south side of the embankment, as the preferred, most technically feasible mitigation measure to achieve a stable embankment and to minimize the post-construction settlements and subsequent maintenance of the new roadway surface. The staged construction approach relies on strength gain in the underlying cohesive deposit to enhance stability of the subsequent stages. The first stage could be constructed up to 5.7 m high with a 1.5 m high by 14 m wide toe berm along the south side of the Highway 17 EBL.

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embankment. The first stage of construction includes the installation of instrumentation to monitor for settlement and pore pressure dissipation and requires a wait period to allow for dissipation of the pore pressures and achieve a strength increase of the cohesive deposit (estimated to be about 14 kPa under the EBL embankment). The actual wait period will be dependent on the results of the monitoring.

After the first wait period is complete, the second stage of construction consisting of a 1.3 m surcharge can be completed and a second wait period will be required to allow for dissipation of the pore pressures of the cohesive deposit to satisfy the settlement criterion. The analysis assumes that the embankment will be "topped up" in the second stage to the final grade prior to placing the surcharge fill. For quantity estimation, additional fill placement of 0.5 m (i.e., second stage total 1.8 m of fill; 0.5 m top up and 1.3 m surcharge fill) for the EBL embankment should be anticipated. The results of the stability analysis for the proposed embankment geometry under the first stage and surcharge stage with the calculated strength gain of the cohesive soils is presented on Figures A24 and A25.

In this case, the up to 0.8 m thick organic deposit will be removed and replaced with granular fill to facilitate installation of the wick drains and the embankment can be constructed of rock fill.

Preliminary analysis using a wick drain spacing of 1.5 m in a triangular pattern to full depth through to the bottom of the cohesive deposit indicates that a wait period of about 10 months would be required for the first stage of embankment construction followed by a surcharge period of about 10 months for a total construction period of about 1.7 years. A detailed wick drain analysis has not been completed on this area and the preliminary analysis of the duration of the wait periods are derived from/based on undrained analyses. As such, the number of construction stages and wait period described above are approximate. The stages of construction, wait periods and estimated settlements are as follows:

Stage	Fill Thickness*	Wait Period	Settlement During Construction	Post Construction Settlement
1	5.7 m	~10 months	110 mm (immediate) 550 mm (primary) 40 mm (rock fill)	-
2 (surcharge)	1.8 m**	~10 months	185 mm (primary) 20 mm (rock fill)	0 mm (primary) 90 mm (creep) 10 mm (rock fill)

*After 0.8 m of peat has been sub-excavated and replaced with granular fill to the original ground surface.

**Includes embankment top up.

After preloading and surcharging for about 1.7 years, the total post-construction settlement at the end of the surcharge period for the Highway 17 EBL embankment is estimated to be 100 mm (comprised of 90 mm creep settlement plus 10 mm long-term rock fill settlement). The result of the settlement analysis for staged construction for the EBL embankment is presented on Figure A26.

The main advantages of this alternative are the significant reduction in the size of the required toe berm to achieve stability compared to non-staged construction as well as the reduced delay in the schedule compared to options where wick drains are not incorporated. The main disadvantage of this option is the increased cost to install and monitor the wick drains and the associated construction wait periods due to the multiple stages.



Further, the actual wait periods are dependent on the results of the monitoring program and could be shorter or longer than estimated.

If wick drains are not utilized for this option, the first stage of construction will require a wait period of about 3 years to allow for dissipation of the pore pressures and achieve the strength increase necessary. The second wait period will require another wait period of about 3 years as the pore pressures dissipate and the necessary strength gain is achieved. The total delay time for construction would be about 6 years. The actual wait periods will be dependent on the results of the monitoring program and could be shorter or longer than estimated.

6.5.1.2.3.2 Surcharging, Wick Drains with Toe Berms

As an alternative to staged construction or the use of EPS, surcharging the Highway 17 EBL embankment, while incorporating wick drains into the clay stratum and a toe berm into the embankment, will achieve stable embankments and minimize the post-construction settlements and subsequent maintenance of the new roadway surface.

Surcharging the embankment increases the load on the underlying soils thereby reducing the delay time required to meet the settlement criterion. Wick drains provide a pathway for the dissipation of excess pore pressure in the cohesive deposit thereby further reducing the time required to meet the settlement criteria. The main disadvantages of this alternative is the large toe berm required (and thus property) on the south side of the embankment, the double handling of the surcharge material and the cost of designing and installing the wick drains, including an instrumentation and monitoring program.

A 2.0 m surcharge above the final profile grade will reduce the time required for preloading and decrease the long-term post-construction settlement including creep. In this case, the up to 0.8 m thick organic deposit will be removed and replaced with granular fill to facilitate installation of the wick drains and the embankments can be constructed out of rock fill.

The maximum stable embankment height for the Highway 17 EBL is 3.4 m. However, for the final embankment plus surcharge height of 7.7 m, a toe berm will be required to enhance stability of the surcharged embankment to a FoS equal to or greater than 1.3. The toe berm required to the south of the Highway 17 EBL embankment is 25 m wide and 2 m high above ground surface.

Preliminary analysis of consolidation of the cohesive deposit under the embankment enhanced by wick drains spaced at 1.5 m in a triangular pattern to full depth through to the bottom of the cohesive deposit indicates that 90 per cent of primary consolidation would be completed in about 10 months. After surcharging for 10 months, the total post-construction settlement is estimated to be 100 mm (90 mm creep settlement plus 10 mm long-term rock fill settlement).

To facilitate the assessment for the end of the surcharge period, instrumentation and monitoring during and after construction will be required. A detailed wick drain analysis has not been completed on this area and the preliminary analysis that the wait period is derived from in this report is based on undrained analyses. As such, the above number of stages and wait times are approximate. Further, the actual wait period is dependent on the results of the monitoring program and could be shorter or longer than estimated.



6.5.1.2.3.3 Full Sub-Excavation and Preloading

Taking into consideration the depth to the bottom of the clay deposit (i.e., up to about 10.4 m below the existing ground surface), full sub-excavation of the cohesive deposit is not considered practical for High Fill Area H1 due to: the potential requirement for specialized drag-line equipment; the substantial time and costs required to complete the sub-excavation and backfilling activities; the need for extra rock fill; the increase in long-term settlement of the thicker zone of rock fill; and the requirement for preloading for 12 months to reduce the long-term (post-construction) settlement. The full sub-excavation, if adopted, eliminates the risk associated with long-term consolidation settlement associated with the silty clay to clay deposit and the long-term settlement of the rock fill after a 12 month preload period is estimated to be 30 mm. It should be noted, however, that the cost of sub-excavation and backfilling may be of the same order of magnitude as some of the other options, including wick drains and staged construction, however, the time to conduct the sub-excavation operations and subsequent preloading may be longer.

6.5.1.2.3.4 Partial Preloading and Lightweight Fill

If there is not sufficient space to accommodate a toe berm, an alternative to reduce the post-construction settlement is to partially preload the embankment and incorporate lightweight (EPS) fill into the embankment mass. The Highway 17 EBL embankment can be constructed to the maximum stable embankment height of 3.4 m without the use of toe berms. After this partial preload period, the Highway 17 EBL embankment will be constructed to the final height by incorporating a 2.5 m thick zone of EPS into the Highway 17 EBL embankment.

After partial preloading for about 3 years (without using wick drains), the total post-construction settlement at the end of the partial preloading period for the Highway 17 EBL embankment is estimated to be 100 mm (comprised of 15 mm remaining primary settlement plus 75 mm creep settlement plus 10 mm long-term rock fill settlement).

The main disadvantage of this option is the substantial cost of EPS fill, which is typically an order of magnitude higher than other fill materials.

6.5.1.2.3.5 Partial Preloading and Lightweight Fill and Wick Drains

In order to reduce the time for consolidation for the alternative of partial preloading and lightweight fill, the use of wick drains has the added advantage of reducing the preload period from about 3 years to about 10 months. In this case, preloading for about 10 months at the maximum stable embankment height of 3.4 m (without the use of toe berms) will be required prior to installation of 2.5 m of EPS.

After partial preloading for about 3 years (using wick drains), the total post-construction settlement at the end of the partial preloading period for the Highway 17 EBL embankment is estimated to be 100 mm (comprised of 90 mm creep settlement plus 10 mm long-term rock fill settlement).

The main disadvantage of this option is the substantial cost associated with both the installation of wick drains and EPS fill.



6.5.1.2.3.6 Surcharging with Toe Berms

Surcharging the Highway 17 EBL embankment and incorporating a toe berm into the south side of the embankment will achieve a stable embankment and minimize the post-construction settlements and subsequent maintenance of the new roadway surface.

If surcharging is used without the incorporation of wick drains into the foundation cohesive deposit, a surcharge period of about 2.1 years will be required to reduce the post-construction settlement to the settlement criterion. The estimated total post-construction settlement at the end of the 2.1 year surcharge period is 100 mm (90 mm creep settlement plus 10 mm long-term rock fill settlement). To facilitate the assessment for the end of the surcharge period, instrumentation and monitoring during and after construction will be required.

As discussed in Section 6.5.1.2.3.2, the maximum stable embankment height is significantly lower than the final surcharged embankment height and toe berms are required. The toe berm required to the south of the Highway 17 EBL embankment is 23 m wide and 2 m high above ground surface.

The main disadvantages of this option are the wait time required for surcharging without the use of wick drains and the requirement of large toe berms which may require the purchase of additional property. If the length of the construction schedule is not a consideration this would be the most cost effective option.

6.5.1.2.3.7 Other Mitigation Options

The option of partial sub-excavation is considered not feasible since in this case, wick drains would not be able to be installed through the rock fill backfill and thus, full preloading to reduce post-construction settlement of the remaining clay deposit would still be required. As a minimum, a 12 month preload period would be required for rock fill compression.

The option of ground improvement, consisting of either dry/wet soil mixing or rammed aggregate piers (geopiers) is also considered not feasible since the amount of cement or aggregate required would result in costs far exceeding other options. Further, additional design and bench scale testing would be required to determine the ultimate feasibility of these options and it may be that there would be insufficient strength gain of the clay deposit to make the soil mixing option feasible.

6.5.2 Highway 17 WBL – STA 13+140 to 13+390 Highway 17 EBL – STA 13+140 to 13+390 St. Pothier Road – STA 9+400 9+600 High Fill H2

Between STA 13+140 and 13+390, the WBL and EBL embankments will require a fill embankment up to 5.0 m high above the existing ground surface to achieve the vertical highway profile. The St. Pothier Road embankment will require a fill embankment up to 4.4 m high above the existing ground surface to achieve the vertical highway profile. These three alignments extend across a low lying swampy area with occasional areas of ponded water. A watercourse runs through the middle of the swamp from north to south. Considering the close proximity of these three embankments to one another, that all three of these embankments are on new alignments and the foundation benefits of building these embankments concurrently, these embankments have been combined into one high fill/swamp area (H2).

The subsurface soils along the H2 alignments generally consist of a surficial layer of peat/organics up to 3.6 m thick, underlain by a cohesive deposit of clayey silt transitioning into varved silty clay to clay transitioning to



clayey silt to silt, which in turn is underlain by deposits of silt to sand to gravelly sand. The cohesive deposit is up to about 10 m thick in some locations and extends to depths up to 13.5 m below ground surface. Resistance to dynamic cone penetration and borehole advancement was encountered at depths of up to 20.3 m below ground surface. In some boreholes, typically near the middle of the swamp, refusal was not encountered at depths of up to 25.0 m below ground surface. Details of the subsurface conditions at the Highway 17 WBL, Highway 17 EBL and St. Pothier Road embankments are presented in Sections 4.5, 4.6 and 4.7, respectively, and the stratigraphic profiles are shown on Drawings B1 to B6 in Appendix B.

The simplified stratigraphy and the associated unit weight, strength, deformation and time-rate consolidation parameters employed for the different soil types encountered in this area are summarized in Table 3. Additional details of foundation engineering parameters employed for the cohesive deposits (i.e., clayey silt/silty clay/clay) encountered in H2 are presented on Figure B25 in Appendix B. The piezometric condition used in the analyses is the water table at the existing ground surface.

The critical sections for stability and settlement are located at about STA 13+260 along the Highway 17 WBL and EBL embankments and at about STA 9+480 along the St. Pothier Road embankment, where the proposed embankment heights are 4.4 m, 4.4 m and 2.9 m high, respectively. The cohesive deposit is about 5.5 m, 9.7 m and 9.8 m thick at the WBL, EBL and St. Pothier Road embankment locations, respectively. Although the maximum embankment height was not encountered at this critical section, the thickness of the cohesive deposit governs the results of the analysis for both stability and settlement.

6.5.2.1 Stability

The stability analyses carried out at the critical section indicates that after completion of construction (including removal and replacement of the up to 3.6 m thick organic deposit with rock fill), the embankments will have a Factor of Safety (FoS) less than 1.3 for a deep-seated, global failure surface that would impact the operation of the highway. Therefore, stability mitigation is required in High Fill H2.

6.5.2.2 Settlement

The settlement analysis carried out at the critical section, estimates the short-term settlement of the foundation soils to be 690 mm. This estimated settlement of the Highway 17 EBL embankment is comprised of about 75 mm of immediate settlement due to compression of the cohesionless deposits and about 615 mm of primary consolidation of the 9.7 m thick cohesive deposit.

Based on an average coefficient of consolidation (c_v) of about $2.0 \times 10^{-3} \text{ cm}^2/\text{s}$ estimated for the cohesive deposit, the imposed loading conditions for the approximately 4.4 m high rock fill embankment (EBL) and assuming two-way drainage of the 9.7 m thick cohesive deposit, it is estimated that about 90 per cent of the primary consolidation settlement will be completed in about 3.2 years.

The magnitude of secondary consolidation (creep) settlement for the cohesive deposit is expected to be about 90 mm per log-cycle of time for this area corresponding to about 70 mm over a 20-year period following completion of construction.

In addition, the total settlement of the rock fill embankment itself (based on a 4.4 m high embankment at the critical section plus 3.6 m of rock fill backfill) is estimated to be about 70 mm, with about 50 mm expected to

occur within six months of construction of the embankment, 10 mm occurring during the next six months and about 10 mm expected to occur over the remaining design life of the embankment.

The estimated total settlement of the St. Pothier Road embankment is comprised of about 80 mm of immediate settlement due to compression of the cohesionless deposits and about 425 mm of primary consolidation of the 9.8 m thick cohesive deposit. These values assume that removal and replacement of the up to 3.6 m thick organic deposit with rock fill has been carried out.

Based on an average coefficient of consolidation (c_v) of about $2.0 \times 10^{-3} \text{ cm}^2/\text{s}$ estimated for the cohesive deposit, the imposed loading conditions for the approximately 2.9 m high rock fill embankment (St. Pothier Road) and assuming two-way drainage of the 9.8 m thick cohesive deposit, it is estimated that about 90 per cent of the primary consolidation settlement will be completed in about 3.2 years.

The magnitude of secondary consolidation (creep) settlement for the cohesive deposit is expected to be about 90 mm per log-cycle of time for this area corresponding to about 70 mm over a 20-year period following completion of construction.

In addition, the total settlement of the rock fill embankment itself (based on a 2.9 m high embankment at the critical section plus 3.6 m of rock fill backfill) is estimated to be about 60 mm, with about 45 mm expected to occur within six months of construction of the embankment, 5 mm occurring during the next six months and about 10 mm expected to occur over the remaining design life of the embankment.

Since the total post-construction settlement (primary, creep and rock fill) exceeds the settlement criterion of 100 mm for the EBL and WBL and 200 mm for the St. Pothier Road embankment, settlement mitigation measures are required for the embankments in High Fill H2.

6.5.2.3 Mitigation of Stability Issues and/or Time Dependent Settlements: Embankments Built Concurrently

The presence of the up to about 10 m thick cohesive deposit influences both the stability and the settlement of the 4.4 m high embankments at the critical section. In order to construct the embankments to achieve a FoS greater than or equal to 1.3, and to minimize post-construction settlements, the alternatives presented below can be considered.

The mitigation options discussed in this section are all based on the assumption that all three embankments are built concurrently. Constructing the three embankments concurrently greatly improves the global stability of the embankments during construction. In particular, the St. Pothier Road embankment would essentially act as a toe berm to support the Highway 17 EBL embankment - without the St. Pothier Road embankment, a temporary toe berm extending across the width of St. Pothier Road would be required to maintain the stability of the Highway 17 EBL until the St. Pothier Road embankment is constructed. For practical purposes, we recommend building the embankments concurrently, as detailed in the alternatives below.

The alternatives described have been evaluated and ranked on the basis of the advantages, disadvantages, relative costs and risk/consequences and are summarised in Table B1 in Appendix B. A summary of the settlement results for each alternative is provided in Table 4.

Section 6.5.2.4 discusses the mitigation scenarios where the St. Pothier Road embankment is constructed after the Highway 17 EBL and WBL have been constructed and the mitigation alternatives are ranked in Table B2 in Appendix B.

Given the thick cohesive deposit (the bottom of which is up to 13.5 m below ground surface) and the associated magnitude of primary consolidation settlement (about 615 mm) of the foundation soils under a 4.4 m high embankment, surcharging with wick drains and incorporating toe berms along the embankments into a staged construction schedule is considered the preferred mitigation alternative, provided all three embankments are constructed concurrently.

6.5.2.3.1 Surcharging, Wick Drains and Staged Construction with Toe Berms

We recommend a staged construction approach with surcharging that incorporates wick drains installed into the cohesive stratum and toe berms supporting the embankments, as the preferred, most technically feasible mitigation measure to achieve stable embankments and to minimize the post-construction settlements and subsequent maintenance of the new roadway surface. The staged construction approach relies on strength gain in the underlying cohesive deposit to enhance the global stability of the embankment during subsequent stages. The first stage could be constructed up to 4.4 m high with 2 m high by 10 m wide toe berms along the north side of the Highway 17 WBL embankment and a 2 m high toe berm connecting the Highway 17 EBL embankment to the St. Pothier Road embankment. During the first stage, the St. Pothier Road embankment must be constructed up to 2.9 m high with a 2 m high by 10 m wide toe berm along the south side of the embankment. The first stage of construction includes the installation of instrumentation to monitor settlement and pore pressure dissipation, and requires a wait period to allow for dissipation of the pore pressures and to achieve a strength increase of the cohesive deposit (estimated to be up to about 16 kPa under the EBL embankment). The actual wait period will be dependent on the results of the monitoring.

After the first wait period is complete, the second stage of construction consisting of a 2.0 m surcharge on the Highway 17 WBL and EBL embankments and a 1.0 m surcharge on the St. Pothier Road embankment, can be completed and a second wait period will be required to allow for dissipation of the pore pressures of the cohesive deposit to satisfy the settlement criterion. The analysis assumes that the embankment will be "topped up" in the second stage to the final grade prior to placing the surcharge fill. For quantity estimation, additional fill placement of 0.7 m (i.e., second stage total 2.7 m of fill; 0.7 m top up and 2.0 m surcharge fill) for the WBL/EBL embankments should be anticipated. For the St. Pothier Road embankment, 0.5 m of top up should be anticipated for a total second stage fill of 1.5 m. The results of the stability analysis for the proposed embankment geometry under the first stage and surcharge stage with the calculated strength gain of the cohesive soils is presented on Figures B26 and B27 for the WBL embankment and on Figures B28 and B29 for the and St. Pothier Road, respectively.

In this case, the up to 3.6 m thick organic deposit will be removed and replaced with granular fill to facilitate installation of the wick drains and the embankments can be constructed out of rock fill.

Preliminary analysis using a wick drain spacing of 1.5 m in a triangular pattern to full depth through to the bottom of the cohesive deposit indicates a wait period of about 10 months would be required for the first stage of embankment construction followed by a surcharge period of about 10 months for a total construction period of about 1.7 years. A detailed wick drain analysis has not been completed for this area and the preliminary analysis to estimate the wait periods presented in this report are based on undrained analyses. As such, the

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number of stages and wait periods described above are approximate. The stages of construction, wait periods and estimated settlement are as follows:

Embankment	Stage	Fill Thickness*	Wait Period	Settlement During Construction	Post Construction Settlement
EBL/WBL	1	4.4 m	~10 months	75 mm (immediate) 580 mm (primary) 40 mm (rock fill)	-
	2 (surcharge)	2.7 m**	~10 months	240 mm (primary) 20 mm (rock fill)	0 mm (primary) 95 mm (creep) 5 mm (rock fill)
St. Pothier Road	1	2.9 m	~10 months	80 mm (immediate) 410 mm (primary) 40 mm (rock fill)	-
	2 (surcharge)	1.5 m**	~10 months	75 mm (primary) 20 mm (rock fill)	65 mm (primary) 130 mm (creep) 5 mm (rock fill)

*After 3.6 m of peat has been sub-excavated and replaced with granular fill to the original ground surface.

**Includes embankment top up.

After preloading and surcharging for about 1.7 years, the total post-construction settlement at the end of the surcharge period for the Highway 17 WBL and EBL embankments is estimated to be 100 mm (comprised of 95 mm creep settlement plus 5 mm long-term rock fill settlement). The result of the settlement analysis for staged construction for the EBL embankment is presented on Figure B30.

After preloading and surcharging for about 1.7 years, the total post-construction settlement at the end of the surcharge period for the St. Pothier Road embankment is estimated to be 200 mm (comprised of 65 mm remaining primary settlement plus 130 mm creep settlement plus 5 mm long-term rock fill settlement). The result of the settlement analysis for staged construction for the St. Pothier Road embankment is presented on Figure B31.

The main advantages of this alternative are the significant reduction in the size of the required toe berms to achieve stability as compared to non-staged construction, as well as the shorter schedules for the first and second stages as compared to options where wick drains are not incorporated. The main disadvantage of this option is the increased cost to install and monitor the wick drains and the associated construction wait periods due to the multiple stages. Further, the actual wait periods are dependent on the results of the monitoring program and could be shorter or longer than estimated.

If wick drains are not utilized for this option, the first stage of construction will require a wait period of about 2.5 years to allow for dissipation of the pore pressures and achieve the strength increase necessary. The second wait period will require another wait period of about 2.5 years as the pore pressures dissipate and the necessary strength gain is achieved. The total delay time for construction would be about 5 years. The actual wait periods will be dependent on the results of the monitoring program and could be shorter or longer than estimated.

6.5.2.3.2 Full Sub-Excavation and Preloading

Taking into consideration the depth to the bottom of the clay deposit (i.e., up to about 13.5 m below the existing ground surface), full sub-excavation of the cohesive deposit is not considered practical for High Fill H2 due to: the potential requirement for specialized drag-line equipment; the substantial time and costs required to complete the sub-excavation and backfilling activities; the need for extra rock fill; the increase in long-term settlement of the rock fill; and the requirement for preloading for 12 months to reduce the long-term (post-construction) settlement. The full sub-excavation alternative, if adopted, eliminates the risk associated with long-term consolidation settlement associated with the silty clay to clay deposit and the long-term settlement of the rock fill after a 12 month preload period is estimated to be 30 mm. It should be noted, however, that the cost of sub-excavation and backfilling may be of the same order of magnitude and likely greater as some of the other options, including wick drains and staged construction as no off-site rock fill would have to be supplied to site at an added cost, however, the time to conduct the sub-excavation operations and subsequent preloading would likely be longer.

6.5.2.3.3 Partial Preloading and Lightweight Fill

If there is insufficient space to accommodate toe berms, an alternative to reduce the post-construction settlement is to partially preload the embankment and incorporate lightweight (EPS) fill into the embankment mass. The Highway 17 WBL embankment can be constructed to the maximum stable embankment height of 3.1 m and the St. Pothier Road embankment can be constructed to the maximum stable height of 2.5 m without the use of toe berms. Assuming the St. Pothier Road embankment will be built at the same time as the Highway 17 WBL and EBL embankments and as such would act as a "toe berm" for the Highway 17 EBL embankment, a 4.0 m surcharge could be constructed on the Highway 17 EBL embankment. After the partial preloading of the WBL and St. Pothier Road and the surcharging of the EBL, the Highway 17 WBL and St. Pothier Road embankments would be constructed to the final height by incorporating a 1.5 m and 1.0 m thick zone of EPS into the embankments, respectively. The EBL embankment would not require the use of EPS due to the large surcharge which could be partially removed to achieve the final embankment height.

In this case, the up to 3.6 m thick organic deposit should be removed and replaced with rock fill. In areas where EPS is required (WBL and St. Pothier Road embankments), the embankments should be constructed out of granular fill to facilitate placement of the EPS. The EBL embankment should be constructed of rock fill. The appropriate side slopes should be utilized as per Section 6.2.1.

After partial preloading for about 1.8 years (without using wick drains), the total post-construction settlement at the end of the partial preloading period for the Highway 17 WBL embankment is estimated to be 100 mm (comprised of 30 mm remaining primary settlement plus 65 mm creep settlement plus 5 mm settlement of the above ground rock fill). At the end of the partial preloading period for the St. Pothier Road embankment the total post-construction settlement is estimated to be 200 mm (comprised of 120 mm remaining primary settlement plus 75 mm creep settlement plus 5 mm long-term rock fill settlement).

After surcharging the Highway 17 EBL embankment for about 1.8 years, the total post-construction settlement for the Highway 17 EBL is estimated to be 100 mm (comprised of 20 mm remaining primary and 75 mm creep settlement and 5 mm long-term rock fill settlement).

The main disadvantage of this option is the high cost of EPS fill, which is typically an order of magnitude higher than other fill materials.

6.5.2.3.4 Surcharging, Wick Drains with Toe Berms

As an alternative to staged construction or the use of EPS, surcharging the Highway 17 WBL, EBL and St. Pothier Road embankments, while incorporating wick drains into the clay stratum and constructing toe berms to support the embankments, would achieve stable embankments and minimize the post-construction settlements and subsequent maintenance of the new roadway surface.

Surcharging the embankment increases the load on the underlying soils thereby reducing the delay time required to meet the settlement criterion. Wick drains provide a pathway for the dissipation of excess pore pressure in the cohesive deposit thereby further reducing the time required to meet the settlement criteria. The main disadvantages of this alternative is that large toe berms would be required (and thus property may need to be acquired), the double handling of the surcharge material and the cost of designing and installing the wick drains, including an instrumentation and monitoring program.

A 2.0 m surcharge above the final profile grade for the WBL and EBL embankment and a 1.0 m surcharge for the St. Pothier Road embankment would reduce the time required for preloading and decrease the long-term post-construction settlement including creep. In this case, the up to 3.6 m thick organic deposit would be removed and replaced with granular fill to facilitate installation of the wick drains and the embankments can be constructed out of rock fill.

The maximum stable embankment height without toe berms is 2.9 m for the Highway 17 WBL, for the Highway 17 EBL is 4.4 m and for the St. Pothier Road embankment it is 2.5 m. The embankment plus surcharge height for each embankment is 6.4 m, 6.4 m and 3.9 m, respectively, therefore toe berms would be required to improve stability of the surcharged embankment to achieve a FoS equal to or greater than 1.3. The toe berm required on the north side of the Highway 17 WBL embankment would be 14 m wide and 1.5 m high and the toe berm required on the south side of the St. Pothier Road embankment would be 22 m wide and 1.5 m above ground surface. Also a "toe berm" about 1.5 m above ground surface that connects the Highway 17 EBL and the St. Pothier Road embankments would be required.

Preliminary analysis of consolidation of the cohesive deposits under the three embankments enhanced by wick drains spaced at 1.5 m in a triangular pattern to full depth through to the bottom of the cohesive deposit indicates that 90 per cent of primary consolidation would be completed in about 10 months.

After surcharging for 10 months, the total post-construction settlement of the EBL embankment is estimated to be 100 mm (95 mm creep settlement plus 5 mm long-term rock fill settlement).

After surcharging the St. Pothier Road embankment for 10 months, the total post-construction settlement is estimated to be 200 mm (50 mm primary, 130 mm creep settlement plus 20 mm short and long-term rock fill settlement).

To facilitate the assessment for the end of the surcharge period, instrumentation and monitoring during and after construction would be required. A detailed wick drain analysis has not been completed for this area and the preliminary analysis used to estimate the wait periods presented in this report is based on undrained analyses. As such, the above number of stages and wait times are approximate. Further, the actual wait period is dependent on the results of the monitoring program and could be shorter or longer than estimated.



6.5.2.3.5 Surcharging with Toe Berms

Surcharging the Highway 17 WBL, EBL and St. Pothier Road embankments and incorporating toe berms into the embankments will achieve stable embankments and minimize the post-construction settlements and subsequent maintenance of the new roadway surface. However, without the use of toe berms, the surcharging would take longer.

The maximum stable embankment height without toe berms is 3.3 m for the Highway 17 WBL, for the Highway 17 EBL is 2.4 m and for the St. Pothier Road embankment it is 2.9 m. The embankment plus surcharge height for each embankment is 6.4 m, 6.4 m and 3.9 m, respectively, therefore toe berms would be required to improve the stability of the surcharged embankment to achieve a FoS equal to or greater than 1.3. The toe berm required on the north side of the Highway 17 WBL embankment would be 12 m wide and 1.5 m high and the toe berm required on the south side of the St. Pothier Road embankment would be 20 m wide and 1.5 m above ground surface. Also a "toe berm" about 1.5 m above ground surface that connects the Highway 17 EBL and the St. Pothier Road embankments would be required.

In this case, the up to 3.6 m thick organic deposit will be removed and replaced with granular fill to facilitate installation of the wick drains and the embankments can be constructed out of rock fill.

After surcharging the WBL and EBL embankments for 2.5 years, the total post-construction settlement of the EBL embankment is estimated to be 100 mm (10 mm primary, 80 mm creep settlement plus 10mm long-term rock fill settlement).

After surcharging the St. Pothier Road embankment for 1.5 years, the total post-construction settlement is estimated to be 200 mm (110 mm primary, 80 mm creep settlement plus 10 mm long-term rock fill settlement).

To facilitate the assessment for the end of the surcharge period, instrumentation and monitoring during and after construction would be required.

The main disadvantages of this option are the wait time required for surcharging without the use of wick drains and the requirement for large toe berms which may require the purchase of additional property. If the length of the construction schedule is not a consideration this would be the most cost effective option.

6.5.2.3.6 Other Mitigation Options

The option of partial sub-excavation is considered not feasible since in this case, wick drains would not be able to be installed through the rock fill backfill and thus full preloading to reduce post-construction settlement of the remaining clay deposit would still be required. As a minimum, a 12 month preload period would be required for rock fill compression.

The option of ground improvement, consisting of either dry/wet soil mixing or rammed aggregate piers (geopiers) is also considered not feasible since the amount of cement or aggregate required would result in costs far exceeding other options. Further, additional design and bench scale testing would be required to determine the ultimate feasibility of these options and it may be that there would be insufficient strength gain of the clay deposit to make the soil mixing option feasible.

6.5.2.4 *Mitigation of Stability Issues and/or Time Dependent Settlements: Highway 17 EBL/WBL Embankments Built Independently from the St. Pothier Road Embankment*

Construction of the three embankments concurrently is critical to maintaining stability of the embankments and is also a major factor in choosing the preferred mitigation alternative. Essentially, the St. Pothier Road embankment will act as a “toe berm” for the south side of the Highway 17 EBL embankment. If the St. Pothier Road embankment is not constructed concurrently with the Highway 17 embankments, then the global stability of the proposed 4.4 m high EBL embankment would be compromised. A toe berm would be required on the south side of the Highway 17 EBL embankment with approximately the same dimensions as the proposed St. Pothier Road embankment (i.e., extending over 25 m wide) to support the EBL embankment. Therefore, the number of technically feasible options is reduced when only the Highway 17 EBL and WBL embankments are considered.

As discussed in Section 6.5.2.3, we recommend surcharging in combination with wick drains and toe berms along the embankments integrated into a staged construction schedule as the preferred mitigation alternative, provided all three embankments are constructed concurrently. We do not recommend constructing the St. Pothier Road embankment at a later time as both stability and long-term settlement of the new EBL/WBL embankments would affect roadway performance and likely construction itself. Further, the costs associated with mitigation of all the embankments would be excessive.

If, however, it is not possible to construct the St. Pothier Road embankment at the same time as the Highway 17 EBL and WBL embankments, then the alternative of partial preloading with lightweight fill (EPS) is considered the only technically feasible option to mitigate both the settlement and stability concerns related to the construction of the EBL embankment. Further, if the St. Pothier Road embankment is constructed at a later date, settlement of the cohesive deposit under the new loading would induce settlement under the EBL embankment.

6.5.2.4.1 Partial Preloading and Lightweight Fill

If the construction schedule does not allow for all three embankments to be built concurrently the only technically feasible alternative to reduce the post-construction settlement while maintaining stability is to partially preload the Highway 17 WBL and EBL embankments and to incorporate lightweight (EPS) fill into the embankment mass. The Highway 17 WBL and EBL embankments can be constructed to the maximum stable embankment height of 2.2 m without the use of toe berms. Partial preloading at this embankment height for 1.8 years would be required to allow for sufficient consolidation settlement of the cohesive deposit and settlement of the rock fill prior to the construction of the pavement structure. After the partial preloading of the WBL and EBL, the embankments could be constructed to the final height by incorporating a 3.0 m thick zone of EPS into the embankments.

After partial preloading for about 1.8 years (without using wick drains) the total post-construction settlement in the Highway 17 WBL is estimated to be 100 mm (comprised of 30 mm remaining primary and 65 mm creep settlement and 5 mm long-term rock fill settlement) and the post-construction settlement in the Highway 17 EBL is estimated to be 100 mm (comprised of 20 mm remaining primary and 75 mm creep settlement and 5 mm long-term rock fill settlement).

The St. Pothier Road embankment can subsequently be constructed to the maximum stable embankment height of 2.5 m without the use of toe berms. Partial preloading at this embankment height can then be carried out for 1.8 years to allow for sufficient consolidation settlement of the cohesive deposit and settlement of the rock fill to occur prior to the construction of the pavement structure. A 1.0 m thick zone of EPS would then be required to raise the embankment to the design grade. After completion of the preload period, the total post-construction settlement is estimated to be 200 mm (comprised of 120 mm remaining primary and 75 mm creep settlement and 5 mm long-term rock fill settlement).

The main disadvantage of this option is the substantial cost of EPS fill, which is typically an order of magnitude higher than other fill materials. The construction of toe berms could reduce the amount of EPS material currently specified. Also, wait times could be reduced by incorporating more EPS material into the embankment or utilizing wick drains.

6.5.3 Highway 17 WBL – STA 13+900 to 14+200 Highway 17 EBL – STA 13+900 to 14+200 High Fill H3

Due to the close proximity and overlap of the realigned Highway 17 WBL and EBL embankments and the existing Highway 17 WBL and EBL embankments, these embankments areas have been combined into one high fill/swamp area H3.

Generally, the proposed Highway 17 WBL and EBL embankments overlap the existing Highway 17 WBL and EBL embankments throughout the high fill area with essentially a widening of the existing embankments of up to about 7 m to the north of both the WBL and EBL embankments between STA 13+950 and 14+150. Between about STA 13+900 and 13+950 and between about STA 14+150 and 14+200, there will either be a cut or minimal to no grade raise. Between about STA 13+950 and 14+150, an embankment widening up to about 7 m and a grade raise up to 3.1 m above the existing embankment will be required to achieve the horizontal and vertical highway profile.

The subsurface soils along the WBL and EBL alignments in High Fill Area H3 consist of surficial layers of peat/topsoil or asphalt and embankment fill, underlain by an upper deposit of sand to sandy silt. These upper deposits are underlain by the main cohesive deposit of clayey silt transitioning into varved silty clay to clay transitioning to clayey silt to silt underlain by a silt deposit, which is further underlain by a deposit of sand to sand and silt. The cohesive deposit is up to 16.8 m thick at some locations and extends to depths up to 19.5 m below ground surface. Resistance to dynamic cone penetration and borehole advancement was encountered at depths of up to 28.0 m ground surface. Details of the subsurface conditions for this swamp crossing area are presented in Sections 4.8 and 4.9 and shown on Drawings C1 to C4 in Appendix C.

The simplified stratigraphy and the associated unit weight, strength, deformation and time-rate consolidation parameters employed for the different soil types encountered in this area are summarized in Table 3. Additional details of foundation engineering parameters employed for the cohesive deposits (i.e., clayey silt/silty clay/clay) encountered in H3 are provided on Figure C22 in Appendix C. The piezometric condition used in the analyses is the water table just below the top of the native organic material (Elevation 241.6 m).

The critical section used in the analysis is located at approximately STA 14+100, where the existing embankments are to be widened thus requiring grade raises at the existing north crest of slope of 1.9 m and 3.1 m above the existing ground surface at the toes of the existing WBL and EBL embankments, respectively. At

STA 14+100, the grade raises will be approximately 0.8 m and 1.1 m above the existing highway grade at the new centrelines of the WBL and EBL, respectively. Boreholes drilled in the WBL and EBL embankments encountered up to 4.7 m and 5.5 m of existing fill, respectively. At this location, the cohesive deposit is up to 14.0 m thick.

6.5.3.1 Stability

At the critical section as described above, the FoS for slope stability would be greater than 1.3 for granular fill or rock fill embankments constructed on the existing fill and subsoils, provided that all organics have been removed below the widened embankment footprint, as shown on Figures C23 and C24 in Appendix C.

6.5.3.2 Settlement

To estimate the magnitude of the expected settlements due to new construction, analysis was carried out at the critical section representative of the subsurface conditions within the high fill area, at approximately STA 14+100. The critical section was chosen in the area of the largest embankment widening, which corresponds to the largest stress loading on the subsoils. At the north side of the EBL which is most critical for settlement, the widening of about 6 m creates a grade raise of 3.1 m above the existing ground surface at the crest of the slope and a grade raise of about 1.1 m above the 5.6 m of existing fill at the proposed EBL centreline.

Based on the results of the settlement analysis for the EBL embankment widening, the short-term settlement of the foundation soils under approximately the new outside edge of pavement (assumed to be the edge of the travelled lane in this analysis) is estimated to be about 115 mm. This estimated settlement in the Highway 17 WBL is comprised of about 25 mm of immediate settlement due to compression of the cohesionless deposits and about 90 mm of primary consolidation of the 14.0 m thick cohesive deposit.

Based on an average coefficient of consolidation (c_v) of about $2.0 \times 10^{-3} \text{ cm}^2/\text{s}$ estimated for the cohesive deposit, the imposed loading conditions for the approximately 3.1 m grade raise and assuming two-way drainage of the 14 m thick cohesive deposit, it is estimated that about 90 per cent of the primary consolidation settlement will be completed in about 6 years.

The magnitude of secondary consolidation (creep) settlement for the cohesive deposit is expected to be about 100 mm per log-cycle of time for this area corresponding to about 60 mm over a 20-year period following completion of construction (i.e., from 6 years to 20 years).

If rock fill is utilized for the embankment widening, the total settlement of the rock fill embankment itself (based on 3.1 m grade raise at the critical section) is estimated to be about 25 mm, with about 15 mm expected to occur within six months of construction of the embankment, 5 mm occurring during the next six months and about 5 mm expected to occur over the remaining design life of the embankment. If granular fill is utilized, settlement of properly placed and compacted granular fill is estimated to occur quickly during construction with no post-construction settlement.

Since the total post-construction settlement is estimated to be about 175 mm (comprised of 90 mm primary consolidation, 60 mm of creep and 25 mm rock fill settlement – if utilized), and exceeds the settlement criterion of 50 mm for an embankment widening, settlement mitigation measures are required for the Highway 17 WBL.