Design, Construction and Long-Term Performance of a Major Highway Embankment Reconstructed using Tire Derived Aggregate (TDA)

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ABSTRACT
In 2007, Tire Derived Aggregate (TDA) was used as lightweight fill to repair a very significant embankment failure of a four-lane divided highway leading to the Canada-U.S. border crossing in St. Stephen, New Brunswick. The highway embankment was under construction when it failed at a height of 12.3 m just short of the design height of 14 m. The cause of the failure was attributed to the rapid rate of construction and the intensity of the embankment loading on the low-strength foundation soils, consisting of 15 m of soft marine clay. The reconstruction strategy used TDA lightweight fill from 1.4 million scrap tires, and a system of prefabricated vertical drains installed through the marine clay over the original failure location. The reconstruction process was staged and controlled using geotechnical instrumentation and the observational approach. The reconstructed TDA embankment was successfully completed to the original design height in 2008 and continued to be monitored into 2009. From the perspective of TDA volume, this project was the largest TDA embankment in Canada and the second largest in North America at the time of construction. This TDA highway embankment has been open to the general public and in full operation since 2008.

In 2020, twelve years after construction, the owner and original designers have gone back to the site to assess the long-term performance of the TDA embankment and compare against the 2008/2009 performance data and the original design assumptions. This case study reviews the design, construction and long-term performance of the TDA highway embankment from the perspectives of the owner and the designers. The long-term performance results show that the TDA highway embankment and pavement continues to perform in general accordance with the original design assumptions.

RÉSUMÉ
En 2007, l'agrégat dérivé des pneus (TDA) a été utilisé comme remblai léger pour réparer une panne de remblai très importante d'une autoroute à quatre voies divisées menant au passage frontalier Canada-États-Unis à St. Stephen, au Nouveau-Brunswick. Le remblai de l'autoroute était en construction lorsqu'il est échoué à une hauteur de 12,3 m juste en dessous de la hauteur de conception de 14 m. La cause de l’échec a été attribuée à la vitesse de construction rapide et à l'intensité du chargement du remblai sur les sols de fondation à faible résistance, constitués de 15 m d'argile marine tendre. La stratégie de reconstruction a utilisé un remblai léger TDA à partir de 1,4 million de pneus usagés et un système de drains verticaux préfabriqués installés à travers l'argile marine au-dessus du lieu de défaillance d'origine. Le processus de reconstruction a été organisé et contrôlé à l'aide de l'instrumentation géotechnique et de l'approche observationnelle. Le remblai TDA reconstruit a été achevé avec succès à la hauteur de conception originale en 2008 et a continué d'être surveillé en 2009. Du point de vue du volume TDA, ce projet était le plus grand remblai TDA au Canada et le deuxième en grandeur en Amérique du Nord au moment de la construction. Ce remblai autoroutier TDA est ouvert au grand public et en pleine activité depuis 2008.

En 2020, douze ans après la construction, le propriétaire et les concepteurs d'origine sont retournés sur le site pour évaluer les performances à long terme du remblai TDA et les comparer aux données de performance 2008/2009 et aux hypothèses de conception d'origine. Cette étude de cas examine la conception, la construction et les performances à long terme du remblai de l'autoroute TDA du point de vue du propriétaire et des concepteurs. Les résultats de performance à long terme montrent que le remblai et la chaussée de l'autoroute TDA continuent de fonctionner en général conformément aux hypothèses de conception d'origine

1 INTRODUCTION

Tire Derived Aggregate (TDA) is a viable lightweight engineered fill material for use on projects such as highway embankments constructed over soft foundation soils. TDA is created from the shredding of scrap tires into sizes ranging from 50 millimetres to 300 millimetres. Standard practice guidelines for the use of scrap tires in civil engineering applications are available.

In 2007, TDA from 1.4 million scrap tires was used to repair a very significant embankment failure of a four-lane divided highway leading to the Canada-U.S. border crossing in St. Stephen, New Brunswick. The embankment was under construction when it failed. The cause of the failure was attributed to the rapid rate of construction and the intensity of the embankment loading on the low-strength foundation soils, consisting of 15 m of soft marine clay. The reconstruction strategy consisted of a 5.5 m thickness of TDA and a system of prefabricated vertical drains installed through the marine clay over the original failure location. The reconstruction process was staged and controlled using geotechnical instrumentation. Geotechnical instrumentation allowed an observational approach to design and construction of the embankment. This was essential to maintain embankment stability on the previously failed foundations soils. Findings and observations verified design assumptions and guided the progress of construction. Modifications to the original design were required and the effects measured by instrumentation.

The TDA embankment reconstruction project began in 2007 and was successfully completed in 2008 with additional field performance measurements taken into 2009. At the time of construction, this project was the first TDA project in Atlantic Canada, the largest TDA embankment in Canada, and the second largest embankment project in North America in terms of TDA volume.

In 2020, twelve years after construction, the owner and original designers have gone back to the site to assess the long-term performance of the TDA embankment and compare against the original 2008/2009 performance findings and the original design assumptions.

This case study reviews the design, construction and long-term performance of the TDA highway embankment from the perspective of the owner and the designers. The long-term performance results show that the TDA highway embankment continues to perform in general accordance with the original design assumptions.

There are relatively little long-term field performance data for TDA structures available in the literature, and as such, there remains an important need to monitor these structures over extended time frames. This paper provides a valuable case study of the field performance of a large scale TDA embankment over a period of twelve years after construction.

2 EMBANKMENT FAILURE AND REPAIR OPTIONS

The embankment failure occurred in July 2006 during construction of a four-lane divided highway leading to the Canada/USA border crossing in St Stephen, New Brunswick, Canada. The highway embankment was approximately 12.3 metres in height when it failed, just short of the design height of 14 metres.

To asses the cause of the failure and to develop possible repair strategies, a forensic geotechnical investigation was carried out consisting of traditional auger boreholes, cone penetration testing (CPT) and installation of geotechnical instrumentation. The results of the geotechnical investigation concluded that the failure was caused by the rapid rate of construction and the overall intensity of the embankment loading on the low strength foundation soils consisting of 15 metres of soft marine clay. The failure was described as a relatively deep-seated circular slip failure with some lateral spreading. The failure encompassed an area of approximately 130 metres in the longitudinal profile by 60 metres in cross-section. Figure 1 shows the failure from the top surface of the embankment looking west. Figure 2 shows the failed embankment cross-section through the centre of the failure including the modeled failure circle through the marine clay layer.

Figure 1. Embankment Failure Condition, July 2006

Once the failure mechanism was understood, several repair options were evaluated with the goal of allowing reconstruction of the embankment and maintaining the original horizontal and vertical alignment. Several reconstruction options were reviewed such as removal of soft clay and replacement with gravel to stone columns to reducing the embankment loading using geofoam or TDA.

After reviewing various repair options, reconstruction of the embankment using TDA lightweight fill combined with stage construction and prefabricated vertical drains (PVDs) was selected. The TDA option was selected by NBDOT because it was estimated that it would save the province 30 percent of the total cost as compared to the next feasible option (Stone Columns).

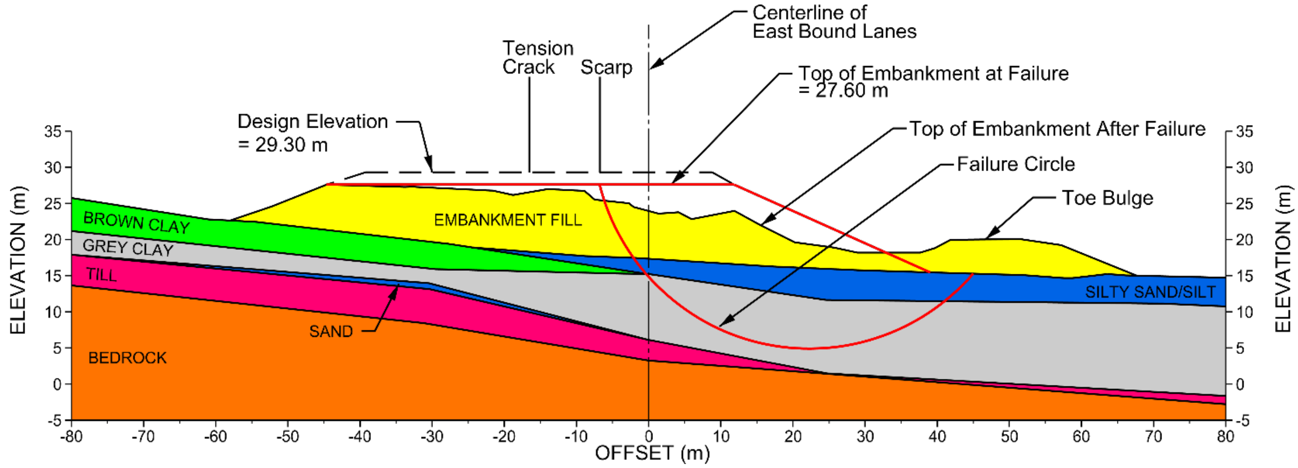

Figure 2. Embankment Cross Section Through Center of Original Failure

The sustainability benefits in using TDA was also important to NBDOT (Mills et al. 2008).

3 DESIGN

The design consisted of a combination of TDA to reduce the embankment loading, prefabricated vertical drains (PVDs) to accelerate consolidation of the underlying clay, and a staged construction approach. Design of the TDA embankment was consistent with the guidelines available in the literature (Humphrey et al. 2000), and ASTM D6270-98 (ASTM 1998). The design included the use of geotechnical instrumentation to allow an observational approach to be conducted by monitoring the behavior of the TDA embankment and underlying foundation soils during the embankment reconstruction process. The design also included contingency strategies due to many unknowns and uncertainties that existed during construction. The TDA embankment as-built cross-section is shown on Figure 3. Several design elements are described as follows:

- The design included 1,750 PVDs at 1.5 metres spacing between drains.
- A 0.5 metres thick sand drain layer was located immediately above the PVDs to allow drainage to be directed downstream to the ditch.
- The embankment was designed using two – 3 metres thick layers of TDA. A total TDA volume of 20,000 m^3 (16,000 tonnes) was originally estimated for the project.
- Type B TDA was specified according to ASTM D6270-08 (ASTM 2008)
- The compressed unit weight of the TDA was predicted to be 800 kg/m^3 or 7.8 kN/m^3.
- Overbuild was considered in the design thickness of the two TDA layers so that the maximum thickness of the TDA after compression would be a maximum of 3 metres each. The bottom and top layers of TDA were designed to accommodate a 13 % and 6 % vertical strain, respectively.
- For serviceability limit states considerations, stage construction was necessary to allow most of the time dependent settlement of the TDA to occur prior to paving.
- The design also considered transitions by tapering of the TDA from the full to zero thickness over a reasonable distance of the order of 6 metres or more. The TDA layers were designed with final slope angles of 2H:1V or flatter.
- The TDA layers were designed to be fully wrapped with woven geotextile (NBDOT Type W3), to act as a separator.
- A minimum 1 metre of low permeable soil cover was used in the design surrounding the TDA. For confinement, the downstream end of the embankment used 2.0 m of low permeable soil.
- A stabilization berm on the downstream side of the embankment was designed to increase the global slope stability of the embankment.
- Both TDA layers were designed with drains at the downstream ends (using 3 % slopes) to allow any water to drain out of the TDA. The drains were designed using well graded granular fill to minimize air infiltration into the TDA.
- The design planned for a 0.9-metre thick surcharge element at the end of the staged construction to maintain this surcharge over the winter season.
- The final asphalt driving surface was designed to accommodate approximately 2.2 metres of separation between it and the top of the TDA. The pavement design consisted of 140 mm asphalt, overlying 150 mm granular base, over 450 mm of granular subbase.
- The exposed surfaces of the embankment were designed with erosion control elements such as vegetative mats, topsoil and hydroseeding, and rip rap surfaces.

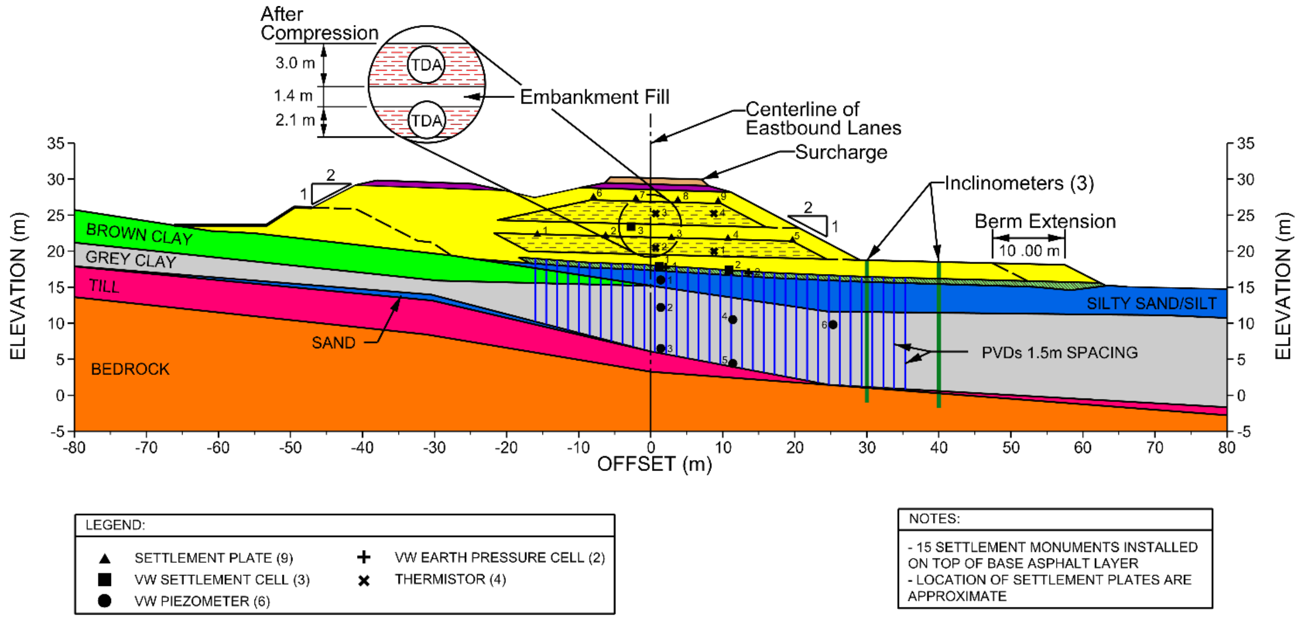

Figure 3. As-Built Cross Section Through Centre of Original Failure Showing Instrumentation

- The design considered an observational approach using the geotechnical instrumentation as shown on Figure 3.

4 SLOPE STABILITY ANALYSIS

Slope stability analysis of the TDA embankment was important at the design and construction stages of the project. The slope stability analysis for the project used the Slope/W commercial software. Slope/W uses limit equilibrium theory to solve for the factor of safety (FOS) of earth slopes. During the design stages, the stability analysis showed the feasibility of the TDA to lighten the load on the previously failed weak clay (with residual strength), assuming a staged construction to full design height. The stability analysis allowed development of minimum undrained shear strength parameters of the clay foundation in order to maintain embankment stability during construction. The geotechnical instrumentation allowed the designers to monitor the excess pore pressure dissipation response in the clay foundation with time, which has a direct function on the undrained shear strength gain.

The original design assumed completion of the embankment over a one-year period using two stages of construction, with two to three weeks holding time predicted between stages. For this project, a minimum FOS of 1.3 was specified during the construction stages (undrained conditions), and a minimum FOS of 1.5 over the long-term (drained conditions). A varying undrained shear strength profile of the marine clay was assumed, with lower and upper bound values varying between 15 to 17 kPa, and 35 to 40 kPa, respectively, depending on the location, depth and construction stage. An angle of internal friction of 20 degrees was assumed for the TDA design.

5 CONSTRUCTION

The TDA embankment reconstruction project took approximately 2 years to complete. Construction started in early June 2007 and was completed in late fall 2008. As stated in the previous section, the construction schedule was originally planned for one construction season, but because of issues with TDA supply, the project was extended over two construction seasons. Figure 3 shows the as-built embankment cross-section including instrumentation lay-out. Monitoring of instrumentation was conducted throughout the reconstruction process. Several highlights concerning TDA construction are provided below:

- Embankment reconstruction started with removal of the failed embankment soils down to approximately original grade in the shape of a “bowl”.
- The failed mass removal was followed by general site grading, compaction, and placement of the sand drainage layer, followed by the installation of the PVDs.
- The Type B TDA was transported from the tire recycling facility in Minto, NB using “floating” floor trailers.
- Following placement of the geotextile, the TDA was placed in 400 mm (loose) lifts using a bulldozer (Figure 4). Each lift of TDA was then compacted using a minimum of 6 passes with a vibratory smooth drum roller with a minimum static weight of 9,000 kg.

- Because of the short supply of TDA, the bottom TDA layer was only constructed 2.4 metres thick instead of the design thickness of 3.45 m. The top layer of TDA was constructed as designed. The reduced thickness of TDA of the bottom layer resulted in a reduction of the total volume from 16,000 tonnes million scrap tires) to approximately 14,000 tonnes (1.4 million scrap tires).
- A layer of low permeable soil cover was placed and compacted on the top and sides of the TDA layers. Construction of the top layer of TDA, low permeable soil cover, surcharge, granular structures, and base asphalt commenced in spring 2008, and was completed in late fall 2008. Because of the various delays over the 2008 construction season, the surcharge was only held for 10 days, so that the base asphalt layer could be completed before winter 2008.
- Settlement plates designed to monitor the immediate and time dependent compression of TDA were disturbed soon after placement. Therefore, only immediate settlement readings were obtained as a result. Settlement monuments on the asphalt surface measured TDA compression and clay consolidation over time.

Figure 4. Placement of Bottom TDA Layer, Aug 2007

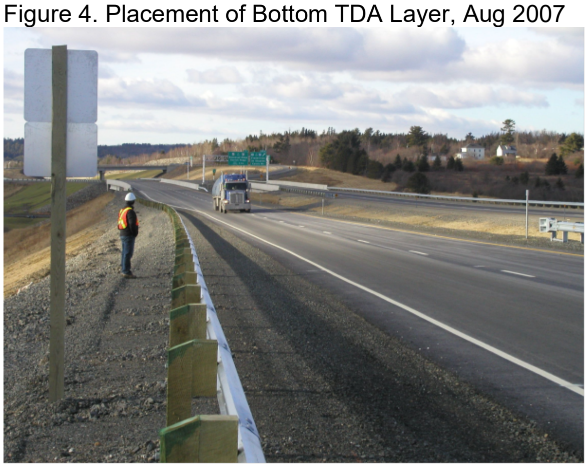

Figure 5. Completed TDA Embankment, Dec 2008

- The completed TDA embankment section of the highway was opened to the public in early December 2008. Figure 5 shows the completed embankment.
- The final asphalt seal layer was placed in May 2009 after majority of time dependent settlement of TDA was completed.

6 OBSERVATIONAL APPROACH DURING CONSTRUCTION

An important element to the design and construction of the TDA embankment repair was the monitoring of the performance of the embankment, foundation and asphalt surface using geotechnical instrumentation. The instrumentation allowed the designers to monitor the behavior of the embankment and foundation, and when required, implement contingency strategies if the performance deviated from the requirements to maintain embankment stability and/or serviceability limit states. Because the embankment already failed and the fact that residual strength of the foundation soils prevailed, the unit weight of the TDA, and performance monitoring of the foundation soil was of primary importance. Also, the TDA was designed using performance parameters and recommendations from the literature, which needed to be confirmed as construction proceeded.

The importance of observing performance of the TDA design is magnified by the large size of the project and because this was the first use of TDA in a highway embankment in the province of New Brunswick. The following examples illustrate the use of the observational approach during the reconstruction process:

- The VW piezometers installed in the centre of the clay foundation layer were used to monitor the effectiveness of the PVDs in accelerating the consolidation process (excess pore pressure dissipation with time). The pore pressure dissipation was important to monitor as it had a direct influence on the undrained shear strength gain in the foundation clay.
- At the halfway point of the embankment construction, CPT was conducted to assess the undrained shear strength (Cu) profile in the underlying foundation clay. The CPT results indicated that the Cu profile directly below the embankment was consistent with predicted values. However, the results showed that the Cu profile downstream of the toe was less than what was required to maintain stability. To maintain the minimum FOS during undrained conditions, the stabilization toe berm was extended 10 m.
- The seal asphalt layer was delayed until majority of the time dependent settlement of TDA occurred. After approximately four months, the base asphalt surface settlement became negligible and the asphalt seal was placed in May 2009.

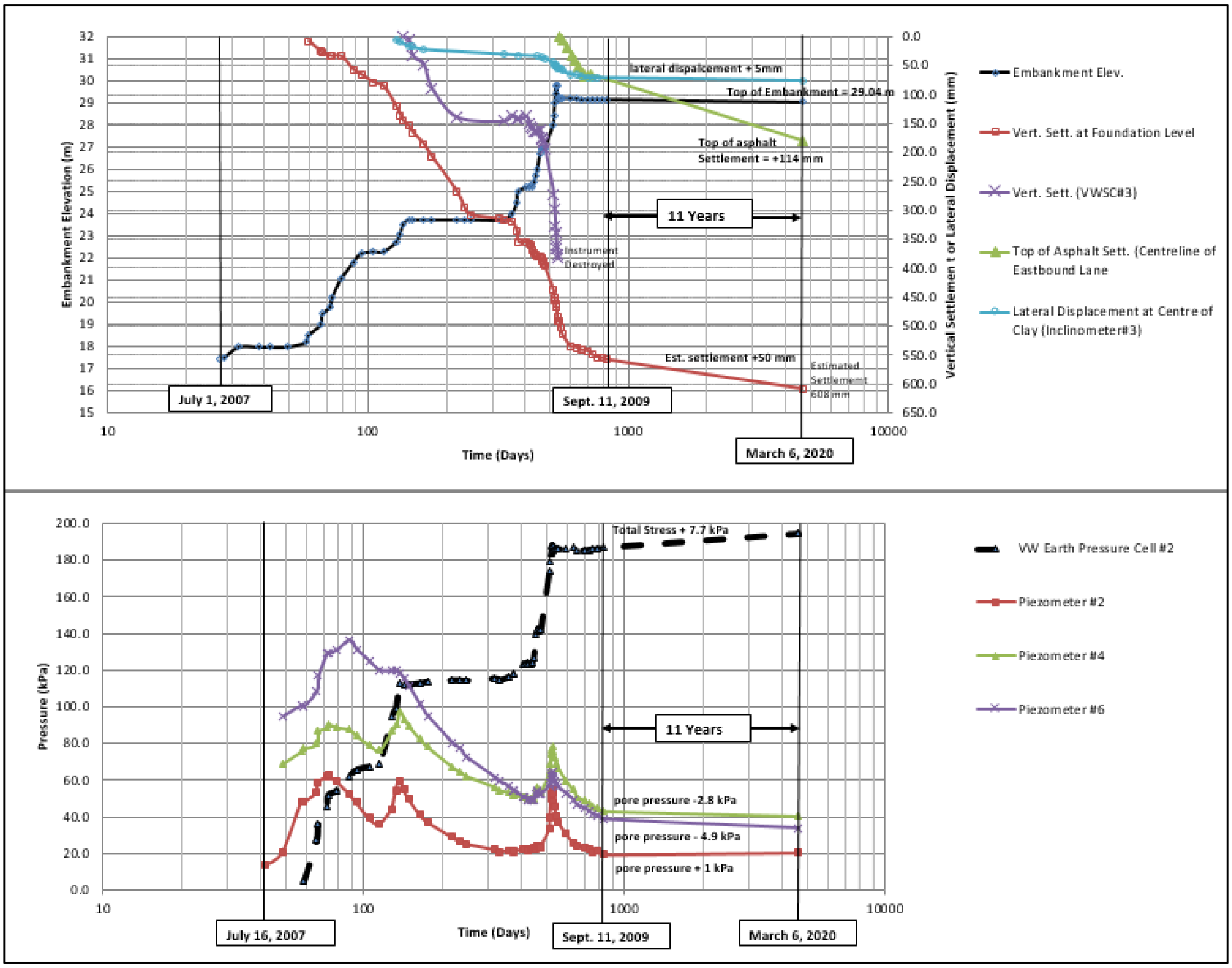

Figure 6. Instrumentation Readings

7 PERFORMANCE DURING CONSTRUCTION

Figure 6 shows the instrumentation readings and TDA embankment and foundation performance over a 27-month period from July 1, 2007 to Sept 11, 2009. It shows the rate of construction and the resulting total stress increase at the foundation level, pore pressure response in the underlying clay, vertical settlement at the foundation level and within the embankment, and lateral displacement at the centre of the grey marine clay layer.

The average total stress increase from the embankment loading was measured to be 186 kPa resulting in a total settlement response of 550 mm over the 25-month construction period at the foundation level. The pore pressure in the clay responded to an increase in total stress from the embankment loading and decreased rapidly for the first 50 days after fill placement ceased. The vertical settlement response of the clay was almost immediate upon loading and continued after loading ceased for an additional 70 to 100 days after each loading stage. Top of asphalt settlement results indicated that the asphalt surface settled approximately 70 mm over a period of five months, and then became negligible.

8 LONG-TERM PERFORMANCE

The long-term performance of the TDA embankment in 2020, twelve years after construction, was assessed using the following four methods:

- Visual review of the embankment slopes and toe areas of the TDA embankment,
- Review of 2020 instrumentation data and comparing against the 2008/2009 instrumentation results,
- Review of 2020 top of asphalt survey data of the TDA embankment and comparing against survey results from 2008/2009; and
- Review of available 2019 pavement condition assessment data of the east-bound lane above the TDA embankment and comparing against areas outside of the TDA embankment footprint. Pavement condition performance indicators reviewed included roughness, rutting, and surface distress.

8.1 2020 Visual Review of TDA Embankment

The owner and designers returned to the site in January 2020 (Figure 7) and again in March 2020 to review the condition of the TDA embankment. There were no signs of embankment instability, cracks, slumps or erosional features and the TDA embankment appears to be performing as designed.

8.2 2020 Review Instrumentation Data

As shown on Figure 6, the March 6, 2020 instrumentation data compared to the readings on Sept. 11, 2009 show the following:

- Over the past eleven years, the pore pressures in the marine clay layer below the TDA embankment have decreased as much as 5 kPa.

Figure 7. TDA Embankment, Jan 2020

  These findings are consistent with continued drainage and dissipation of excess pore pressures in the clay returning to a long-term drained condition. This dissipation of excess pore pressures in the foundation clay resulted in additional consolidation settlement of the embankment over the past eleven years.
- Since the pore pressures and embankment have returned to a long-term drained condition, the total stress at the foundation level has correspondingly increased by approximately 8 kPa from 186 kPa to 194 kPa.
- The total lateral displacement measured in the centre of the marine clay layer was 76 mm on March 6, 2020, an increase in 5 mm since 2009. This lateral displacement is as a result of consolidation settlement in the foundation clay.
- The VW settlement cell data retrieved on March 6, 2020 are considered erroneous and unreliable, so the data was not included on Figure 6. The likely sources of error are related to the lack of liquid maintenance of the VW settlement cells over the past 12 years.
- Settlement of the embankment at the foundation level has been estimated based on the 2020 top of asphalt survey and the 2020 lateral displacement measurements described above. It is estimated that the TDA embankment at the foundation level has settled an additional 50 mm over the past eleven years for a total of 608 mm.

8.3 2020 Review of Top of Asphalt Survey Data

The top surface of the asphalt along the centreline of the east bound lane was surveyed in May 2020 and compared to the 2008 and 2009 survey results. Figure 8 shows the vertical settlement of the top surface of the asphalt over 2008 and 2009 compared to the May 2020 survey results. Figure 9 shows the east bound lane profile in May 2009 compared to May 2020.

The survey results show that the top of asphalt above the TDA embankment settled between 110 mm and 114 mm over an eleven-year period. It is estimated that 50 mm of the 114 mm settlement is from TDA secondary compression, plus 50 mm from consolidation settlement of the foundation clay, and the remaining 10 mm to 14 mm is from consolidation settlement of the embankment fill.

The settlement of the top of asphalt outside of the TDA embankment settled 63 mm over the same eleven-year period. It is estimated that 50 mm of the 63 mm is from consolidation settlement of the foundation clay, and the remaining 13 mm is from the embankment fill consolidation settlement.

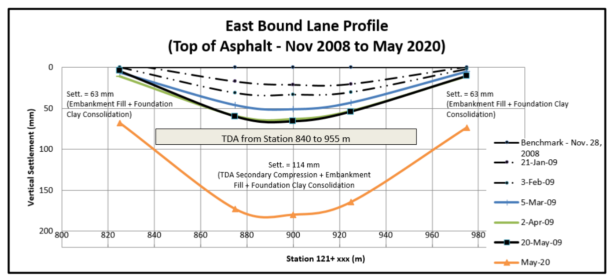

Figure 8. Settlement of Asphalt Surface over Time

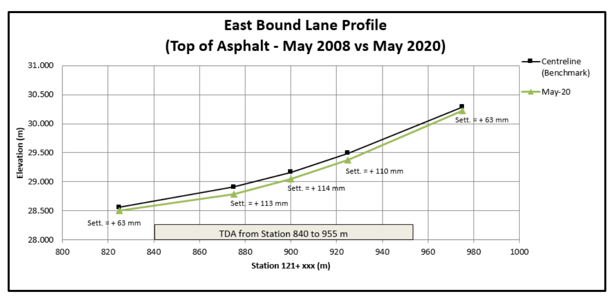

Figure 9: East Bound Lane Profile

8.4 2019 Review of Pavement Condition Data

A pavement condition inspection of the highway is carried out every 2 years by Applied Research Associated (ARA) on behalf of Gateway Operations Limited, the company that carries out maintenance of the highway. The detailed pavement condition inspections are completed using a Digital Survey Vehicle (DSV) that is equipped with digital cameras that captures images of the pavement and right-of-way, and a set of lasers mounted in the front bumper. All data collected by the DSV is georeferenced using a global positioning system. The data is compiled and reported as the average within 100 m increments.

The pavement condition data reported by ARA for the east-bound lanes over km 9.4 to 9.6 associated with the TDA embankment is summarized in Table 1. The results in Table 1 show that the pavement condition ratings of the highway over the TDA section is consistent with the pavement condition ratings outside of the TDA embankment footprint. The pavement condition results meet the pavement standards and key performance indicator limits required for this provincial highway. Therefore, the asphalt pavement over the TDA embankment section from the perspective of pavement condition continues to meet design expectations after 12 years of service.

Table 1. 2019 Pavement Condition KPI Results

Key Performance Indicators, KPI	Over TDA Section	Outside of TDA Section (within 0.5 km)
Roughness[1] (m/km)	0.79 to 1.11	0.62 to 1.83
Rutting[2] (mm)	1 to 5	2 to 11
Surface Distress[3]	9.5 to 9.9	8.6 to 10.0

[1]IRI: International Roughness Index shall not exceed 2.28 m/km
[2]Rut: Rutting depth shall not exceed 20 mm
[3]SDI: Surface Distress Index shall not fall below 7.9

9 PREDICTED VERSUS MEASURED VALUES

The original design or predicted parameters compared to the field measured values in 2009 and 2020 are summarized in Table 2 below.

Table 2. Design versus Field Measured Values

Parameter	Design or Predicted	Field Measured (2009)	Field Measured (2020)
Settlement at Foundation	600 mm	558 mm	608 mm (Estimated)
Lateral Displacement	60 mm	71 mm	76 mm

In general, the design or predicted values were very close to the field measured values just after construction in 2009 and in 2020. Based on the above review, the TDA embankment continues to perform in 2020, twelve years after construction.

10 LESSONS LEARNED

From the perspective of the owner of the highway (NBTI) and the designers of the TDA embankment, the following lessons learned are provided:

- The success of the TDA embankment project was attributed to many factors. The design and construction were carefully planned and staged with specific contingency strategies to manage the uncertainties and risks during the construction process.
- The performance of the TDA embankment and foundation clay layer were monitored using geotechnical instrumentation. This observational approach was essential to the success of the project.
- From NBTI's perspective, public and fire safety were important considerations in the rural setting of the site requiring full-time security to manage this risk.
- The lightweight embankment repair solution required the beneficial lightweight properties of TDA. This made the "scrap tire" materials a valuable commodity that resulted in significant savings to the taxpayer compared to other lightweight fill alternatives such as geofoam.
- TDA supply can be an issue on projects requiring significant TDA volumes. Securing the supply of the TDA volumes well in advance of construction is recommended on projects that require a significant volume of TDA.
- Many smaller projects can also benefit from the beneficial properties of TDA such as integral bridge abutment backfill, frost heave road repairs, cover over deep fill culverts, and compressible materials for induced trench applications.
- Maintenance of specialized instrumentation such as VW settlement cells should be given special attention for embankment structures that may be monitored over the long-term.

11 CONCLUSIONS

The TDA lightweight fill highway embankment was successfully constructed and opened to the public in Dec. 2008. In 2020, twelve years after construction, the overall performance of the TDA embankment and asphalt pavement continues to meet the design requirements and expectations.

During construction, the observational approach using geotechnical instrumentation was essential to the success of the project. It allowed the designers and owner the ability to confirm the behavior of critical components of the design during construction and confirm the long-term performance twelve years after construction.

This paper provides a valuable case study of design, construction and long-term performance of a large scale TDA lightweight fill highway embankment constructed over soft marine clay soils for a period of 12 years after construction.

12 REFERENCES

ASTM 2008. Standard practice for use of scrap tires in civil engineering applications, *D 6270-08*, West Conshohocken, Pa.

Humphrey, D.N. Whetten, N., Weaver, J., Recker K. 2000. Tire shreds as lightweight fill for construction on weak marine clay, *Proc., Int. Symp. On Coastal Geotechnical Engineering in Practice,* Balkema, Rotterdam, The Netherlands, 611-616.

Mills, B. and McGinn, J. 2008. Recycled Tires as Lightweight Fill, *Recycled Materials and Recycling Processes for Sustainable Infrastructure Session of the TAC Annual Conference,* Toronto, ON.