Innovative Structural and Geotechnical Strategies: Crossing Unstable River Valleys in Northern Alberta

Neil Robson, M. Eng., P.Eng., Principal, DIALOG™, Edmonton, Canada

Gamal Ghoneim, M.Sc., P.Eng., Associate, DIALOG™, Calgary, Canada

Don Proudfoot, M.Eng., P.Eng., Principal, Thurber Engineering Ltd., Edmonton, Canada

Donald Saunders, P.Eng., Bridge Manager, Alberta Transportation, Peace River, Canada

Darcy Taylor, P.Eng., Manager, Transportation Infrastructure, ARA Consulting Engineering Ltd., Calgary, Canada

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Abstract: Located north of the City of Grande Prairie and west of the Town of Spirit River in northwest Alberta, Highway 727 serves local farm residents, oilfield activities, and businesses. Generally speaking, the terrain along the 18 km long highway is flat with the exception of the Ksituan River and Howard Creek crossings, which have valley depths of 70 to 80 m.

Geotechnically unstable, these valleys have experienced regular slide activities along the highway for over 30 years. Repair and maintenance measures have not been able to resolve the geotechnical instabilities, and slide movements were occurring at an increasing rate. In 2005 the Province of Alberta made the decision to realign Highway 727.

The chosen alignment for the new highway provided improvements in a number of areas including roadway geometrics, environmental impact, and utility coordination issues. However, the new alignment still required crossing structures at the Ksituan River and Howard Creek. With large slide blocks in the valley slopes and weak compressible subsurface clay, bridges or traditional culvert crossings would not be technically or economically feasible at these locations. An innovative and creative engineering solution was required that would efficiently solve the technical problems at the sites, would be constructable, and would provide safety and value to the citizens of Alberta.

Presented as a case study, the paper describes the matrix process that was used during preliminary design to evaluate various options for the crossing structures. For each potential highway gradeline, appropriate types and lengths of crossing structures, including their corresponding geotechnical issues, were evaluated. The selected option best optimized cost, safety, environmental impact, geotechnical loading, and constructability. It utilized an aggressive highway gradeline that crossed the valleys at right angles, with large cuts to offload the crests, and cast-in-place concrete culverts and embankment fills to buttress the toes of the slopes.

The paper will also focus on the methodology applied to optimize the design of the culvert and mitigate the known geotechnical issues. Descriptions will be given on the use of driven steel shear piles, wick drains, and lightweight expanded polystyrene (EPS) as embankment fill material, to reduce culvert lengths and anticipated settlements.

Construction techniques for the construction of the culverts, and placement of the EPS blocks are described. Practical recommendations and lessons learned during the design and construction stages are also outlined.

1. Project Background

Located north of the City of Grande Prairie and west of the Town of Spirit River in northwest Alberta, Highway 727 serves local farm residents, oilfield activities, and businesses. Generally speaking, the terrain along the 18 km long highway is flat with the exception of the Ksituan River and Howard Creek crossings, which have valley depths of 70 to 80 m.

Geotechnically unstable, these valleys have experienced regular slide activities along the highway for over 30 years. Repair and maintenance measures have not been able to resolve the geotechnical instabilities, and slide movements were occurring at an increasing rate. Figure 1 shows examples of typical slides along the existing highway which have required repair. In addition to the slide activities, the existing Ksituan River and Howard Creek culverts below the highway were undersized to accommodate drift, in very poor condition, and prone to log jamming and flooding.

Figure 1: Typical Slides along Existing Highway 727 Requiring Repair

Due to these issues, Alberta Transportation made the decision in 2005 to realign Highway 727 in order to facilitate the replacement of the Ksituan River and Howard Creek culvert crossings and to construct a more stable road alignment that could be paved in the future without excessive maintenance costs to address the geotechnical instabilities. This decision was made because the long-term costs of reconstructing the highway along a new alignment were estimated to be less than trying to replace the culvert structures, paving the highway on the existing alignment, and continuing to repair the slide activities that were occurring annually.

The chosen alignment for the new highway provided improvements in a number of areas including roadway geometrics, environmental impact, and utility coordination issues. However, the new alignment still required crossing structures at the Ksituan River and Howard Creek valleys. With large slide blocks in the valley slopes and weak, compressible subsurface clay, bridges or traditional culvert crossings would not be technically or economically feasible at these locations. An innovative and creative engineering solution was required that would efficiently solve the technical problems at the sites, would be constructable, and would provide safety and long-term value to the citizens of Alberta.

2. Geotechnical Investigation and Preliminary Recommendations

A preliminary geotechnical investigation, consisting of four test holes at each crossing site, had previously been completed for Alberta Transportation in 2005. Slope inclinometers and pneumatic piezometers had also been installed in selected test holes to monitor slide movements and porewater pressures. To supplement this previous work, a more extensive investigation program was completed by the Consultant team in 2006. The additional investigation included drilling numerous test holes within the Ksituan River and Howard Creek valleys and the proposed upland approach cut sections. Figure 2 shows the typical site conditions at the Howard Creek prior to construction, including a very steep bank showing evidence of slide failures. Drill rig access to the sites required clearing and construction of access roads, benches, and drill pads in the valley sections.

Figure 2 – Existing Site Conditions at Howard Creek

Once sufficient site access was created, test holes were drilled along the creek bank, to depths ranging between 15 m to 33 m below existing ground surface. This included continuous soil cores at two locations along the alignment of each watercourse. The test holes in the uplands ranged from 10 to 30 m in depth. The locations of the test holes were spread apart and selected to provide details for the slope cross-sections used for global slope stability analyses. Pneumatic piezometers were installed in three of the test holes and standpipe piezometers were installed in two test holes.

Laboratory testing included a visual classification and determination of natural moisture content of each soil sample. A detailed visual review of the cores was also completed. Additional laboratory testing included Atterberg Limits, grain size analyses, water-soluble sulphate content determinations, pH tests and soil resistivity tests. Electrical conductivity and pH tests were also carried out on a river water sample.

The results of the geotechnical investigation and testing program revealed that the soil conditions within the valleys at the Ksituan River and Howard Creek crossing sites generally consisted of lacustrine clay overlying high plasticity clay till overlying medium to high plasticity laminated clay of variable stiffness. On the valley slopes these materials were covered by a mantle of colluviums (slide debris). Clay shale bedrock was present at a depth of at least 20 m below the creek/river beds. Preliminary geotechnical analysis identified that slope stability would be a major concern for any crossing structure due to the presence of active slide blocks and pre-sheared clay layers in the valleys.

A preliminary assessment of selected structure types was conducted to determine if they would be feasible options for the Ksituan River and Howard Creek crossings. A long, multi-span bridge structure spanning across the valley was assessed at each site, as was a large diameter culvert buried beneath a deep fill soil embankment.

The presence of existing active landslides on both sides of the valleys made a bridge structure an unlikely alternative for the crossings. Extensive reinforcement of the valley slope with large piles to anchor the slide blocks in place would be required for a bridge alternative. Additional instrumentation would also be required to gain a better understanding of the limits of the slide blocks and their perspective slip planes in order to complete the detailed bridge design.

The large diameter culvert was considered to be a feasible alternative, since the embankment over the culvert would provide additional buttressing support and constraint to prevent further movement of the slumps on the valley slopes. An embankment side slope inclined at 4.5H:1V was recommended to achieve an appropriate factor of safety for slope stability. Additional stability measures were also recommended for the toe of the embankment side slope in the vicinity of the culvert inlet and outlet structures including either the use of a shear pile wall or a grid of stone columns.

3. Evaluation of Conceptual Alternatives

The first step of the design process was to evaluate several conceptual options for the crossing structures at each valley. The purpose of this first step was to eliminate any options that were not viable, and to reduce the number of options that would be assessed in greater detail. A total of five different options were initially evaluated for the selected highway gradeline. These options included a multi-span bridge, a culvert with soil embankment and full sideslopes, a culvert truncated by tall wingwalls and headwalls with a soil embankment, a shortened culvert with sideslopes truncated by vertical mechanically stabilized earth (MSE) walls, and a pair of braced walls parallel to the watercourse capped at the top by a culvert. For illustrative purposes, Figure 3 shows an elevation view of the mutli-span bridge option and a plan view of the shortened culvert with sideslopes truncated by vertical MSE walls.

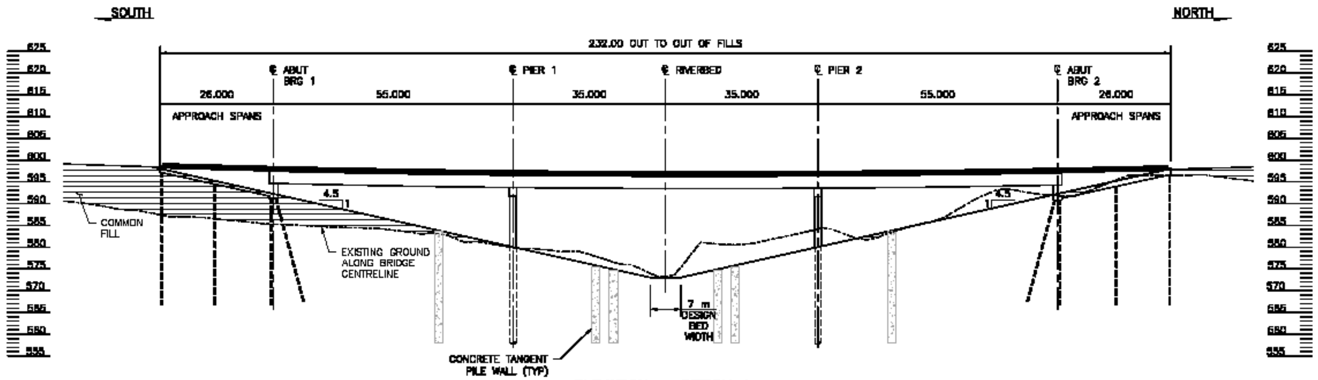
Each of the options was ranked within nine different project categories; each category weighted based on its relative importance to the project. The ranking ranged from 5 being excellent to 1 being poor. The sum of the weighted rankings was compared to assess the relative performance of each alternative.

The categories used to evaluate the structures are described below:

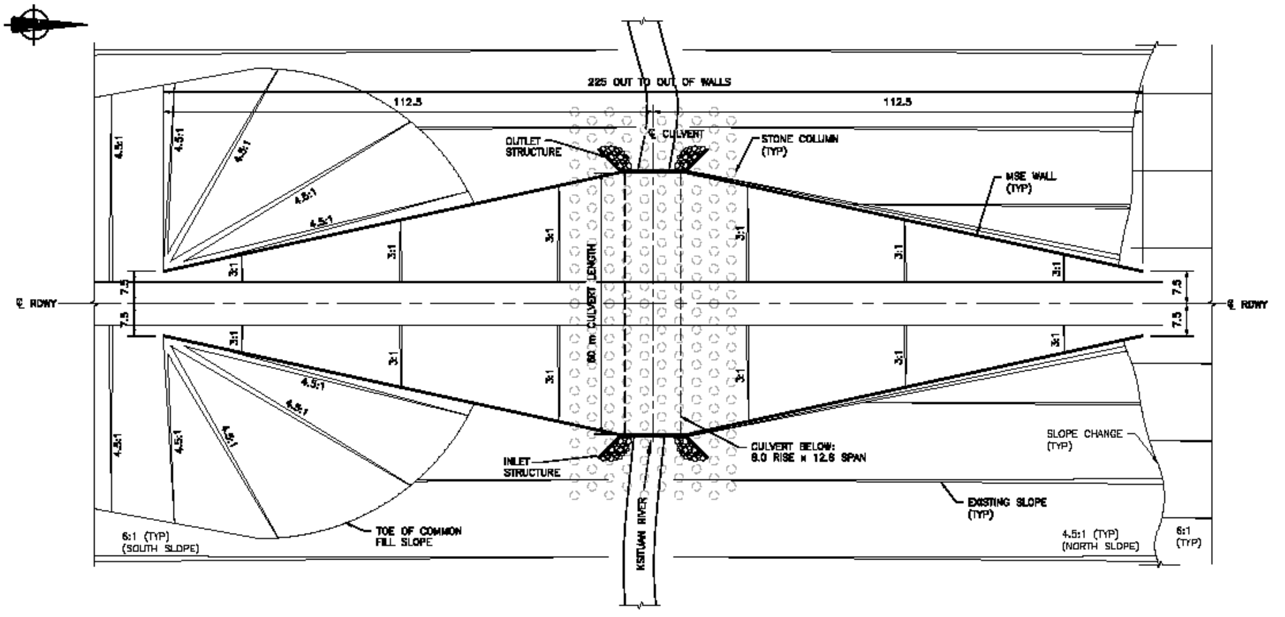
- **Construction Cost**: Initial cost of construction and design.
- **Life-Cycle Cost:** Total life cycle costs of the structure for a 75-year design life. Includes annual maintenance and major rehabilitation costs.
- **Constructability:** Ease and practicality of construction. Includes allowance for the amount of perceived construction risk to a Contractor.
- **Geotechnical:** The amount of geotechnical stabilization work required to build the structure. Includes consideration of the risk of future geotechnical instability on the performance of the structure.
- **Overall Safety Upon Completion:** Effect of structure on long-term safety of traffic. Includes impact on animal / vehicle interaction.
- **Hydrotechnical:** Effect of structure on hydrotechnical performance of the waterway.
- **Impact on Environment:** Extent to which the existing environment surrounding the structure will be disturbed. Includes consideration of animal passage through valley and fish passage through the structure.
- **Construction Schedule:** Anticipated length of construction.

- **Environmental Approvals:** The process required to gain approval for construction from regulatory authorities. Includes consideration of any habitat compensation required.

After completing the initial evaluation process, the shortened culvert option with sideslopes truncated by vertical MSE walls was the highest ranked, did not receive a score lower than 4 in any of the categories, and was the lowest cost option. However, the cost estimates for all of the options were substantially higher than the available budget and previous cost estimates. A substantial component of each cost estimate was the soil stabilization and mitigation measures associated with the large fill heights and poor geotechnical conditions at each site.



ELEVATION – OPTION 1
BRIDGE
1:750



PLAN VIEW – OPTION 3A
PARALLEL VERTICAL MSE HEADWALLS WITH CULVERT
1:750

Figure 3: Elevation View – Bridge Option; Plan View – Shortened Culvert Truncated by MSE Walls

4. Alternate Gradeline Assessment

The preliminary assessment of the conceptual options at each valley crossing was based on a 110 km/hr design speed, which was the design standard for the future paved highway. As mentioned in the previous section, the cost estimates for all of the valley crossing structural options were substantially higher than the available budget and previous estimates. This was primarily due to the poor geotechnical conditions at each site, combined with the elevation of the roadway associated with the design standard.

As part of a value engineering exercise, three alternate highway gradelines were examined. Although the gradelines did not meet all requirements of the design standard, they would substantially reduce the elevation of the roadway above the valley floor, and offload the crests of the valleys, without compromising user safety or driving comfort. The resulting reduction in roadway elevation increased the amount of excavation required at each site, and generated a significant amount of surplus material that would have to be disposed of, but also reduced the estimated cost of the structures by over 50%. It was also determined that a concrete culvert with a soil embankment and traditional sideslopes would be the lowest cost structure associated with the lower gradelines, due primarily to a significant reduction in the amount of soil stabilization that would be required with this option.

The total estimated cost associated with each alternate gradeline was then compared to the original design gradeline, accounting for both the increased grading costs and the reduced structure costs of the lower gradeline options. Table 1 below shows the estimated grading cost premiums and structural cost reductions for each of the three alternate options. It was found that revising the highway gradline to accommodate a 90 km/hr design speed, and constructing a culvert at each valley crossing, could achieve an estimated project savings of close to 30% when compared to the original design concept, while still maintaining an acceptable highway design standard.

Table 1: Alternate Gradeline Comparison

<u>Bridge Options</u>

		Overall	Ksituan River	Howard Creek	Overall
Option	Speed-Crest-Sag	Grading Cost Premium (%)	Structural Cost Reduction (%)	Structural Cost Reduction (%)	Project Cost Reduction (%)
Original	110-100-40	0%	0%	0%	0.0%
1	90-55-40	75%	-42%	-35%	9.1%
2	80-35-35	101%	-45%	-62%	14.1%
3	80-100-35	219%	-58%	-52%	-15.2%

<u>Culvert Options</u>

		Overall	Ksituan River	Howard Creek	Overall
Option	Speed-Crest-Sag	Grading Cost Premium (%)	Structural Cost Reduction (%)	Structural Cost Reduction (%)	Project Cost Reduction (%)
Original	110-100-40	0%	0%	0%	0.0%
1	90-55-40	75%	-58%	-57%	27.6%
2	80-35-35	101%	-65%	-78%	32.7%
3	80-100-35	219%	-75%	-73%	7.9%

5. Refined Geotechnical Analysis

Although the lowered highway gradeline combined with culvert option had less geotechnical issues than the original design concepts, the presence of clay below the valley floor that had been pre-sheared by landslide movements would still have a significant effect on the stability of the culvert embankment fill and long term performance of the culvert structures.

It was determined that the overburden pressure created by the highway embankment would result in the generation of high pore pressures in the high plastic foundation soils below the culvert and lead to large long term settlements of the culverts that could decrease the short term stability of the embankment fill. It was recommended to install wick drains on a 1 m triangular grid throughout the footprint of the embankment where fill heights exceeded 6 m to allow faster dissipation of pore water pressures during construction and to accelerate the settlement process.

Foundation settlement and associated lateral spreading also created a challenging design condition as major geometric changes would occur after the construction of the culvert. Initial estimates indicated maximum settlements of up to 700 mm below the culverts based on the use of clay fill in the embankment. In order to reduce the amount of anticipated settlement below the culvert, alternate fill materials and soil reinforcement techniques were investigated. A refined settlement analysis was conducted to evaluate the efficacy of using stone columns below the culvert or using light weight fill material above the culvert. Figure 4 presents the results of the refined analysis indicating that expected settlements could be reduced by roughly 35% if one of these additional measures was used.

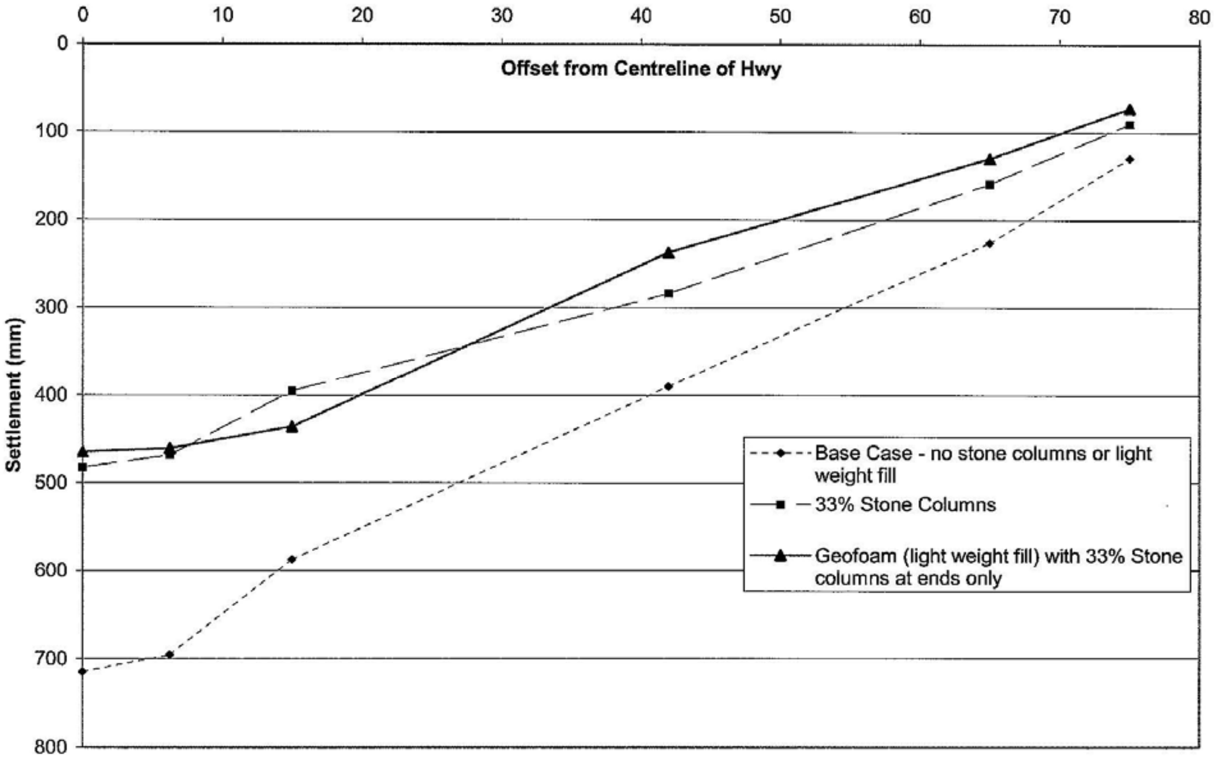


Figure 4: Comparison of Estimated Settlements below Ksituan River Culvert

6. Detailed Design Challenges and Innovations

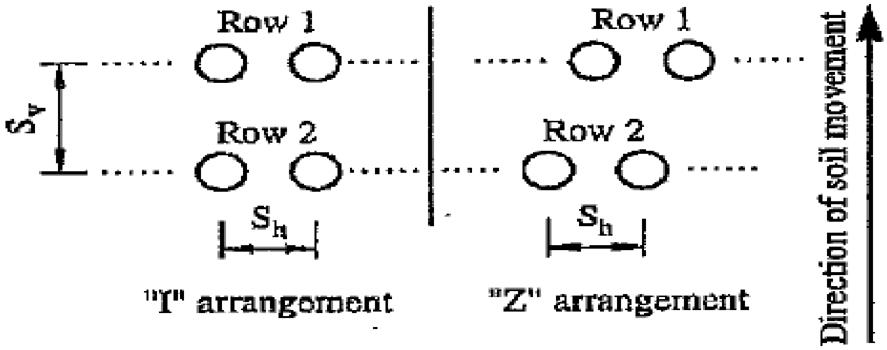
Although the preliminary design phases of the project reduced the magnitude of the known geotechnical issues affecting each culvert, they were not eliminated. Innovative techniques and strategies would be required to improve the stability of the embankment fills and reduce the anticipated settlements below the culverts. Examples of these techniques include the use of driven steel shear piles, wick drains, and lightweight expanded polystyrene (EPS) as embankment fill material.

In addition to the innovative techniques required to mitigate the geotechnical issues, the large size of the culverts warranted as efficient a design as possible. A variety of modelling techniques and approaches were used to optimize the design of the inlet and outlet structures at the ends of the culverts, as well as the main culvert cross section.

6.1 Driven shear piles

Two rows of steel pipe shear piles were installed behind the wingwalls at each end of the culverts, driven to below the measured base slip surface of the landslide block to provide additional horizontal resistance to the earth pressures exacted by the slide blocks on the wingwalls. The pipe piles also provided additional slope stability to the embankment fill sideslopes.

The shear piles were required resist unfactored lateral forces parallel to the direction of the streambed of 300 kN/m at Ksituan River and 500 kN/m at Howard Creek. The piles were designed in pairs and the forces in the piles were estimated based on the work by Chen and Poulous, 1997 (1) for piles arranged in two infinitely long rows. The force distribution on the piles, F_p, was linearly extrapolated from values given by Chen and depended on the spacing between rows of piles S_v, the horizontal spacing between piles S_h, and the pile diameter D.



Case	S_h/D	S_v/D	F_p	
			Row 1	Row 2
Z-1	3	3	1.200	1.100
Z-2	3	6	1.400	1.200
Interpolated	4	3	1.300	1.133
Z-3	6	3	1.100	1.000

Figure 5: Pile Arrangement and Dimensionless Force Distribution on Piles. (Extract from Chen and Poulous, 1997)

The structural design of the shear piles was based on Brom's solution for ultimate lateral resistance of long piles; refer to Das, 1999 (2) and Meyerhof, et al 1988 (3). The design of the piles was also checked based on beam on elastic foundation principles using soil horizontal spring supports and beam elements. Different pile diameters, pile spacing, and pile row spacing were investigated to arrive at the selected spacing and staggered arrangement. The final design utilized pipe piles measuring 508 mm in diameter with a 13 mm wall thickness, spaced at 2000 mm on centre at Ksituan River and 1500 mm on centre at Howard Creek. The two rows of piles, spaced at 1500 mm apart, were constructed by installing one complete row before the second row was started.

6.2 Wick Drains

Wick drains were installed below the higher embankment fill sections to help dissipate construction induced pore water pressures from the foundation clay. The wick drains were installed on a 1 m triangular grid to a maximum depth of approximately 20 m. A total of over 247 000 m of wick drains were installed at the two sites combined. A 600 mm thick free-draining sand layer was placed over the top of the drains to transfer the groundwater from the wick drains to the outer edges of the embankment fills. Subdrains were also used to help collect the water from the wick drains.

6.3 Lightweight Fill Material

To reduce settlements below the culverts and improve their overall stability, lightweight expanded polystyrene (EPS) blocks were substituted for clay fill within the inner core of the embankment fills above the culverts. The EPS blocks had a unit weight of 0.5 kN/m^3, which was over 97% lighter than clay. The blocks were installed in a staggered layer pattern using gripper plates to prevent shifting and maintain alignment between adjacent blocks. The EPS portion of the embankment fill was specifically designed in a trapezoidal shape, as opposed to a rectangular block, in order to create a smoother settlement profile below the culverts, easing the transition between zones with EPS and zones without.

6.4 Inlet and Outlet Structures

The design of the inlet and outlet structures at the ends of the culverts was carried out using conventional retaining wall design methods based on earth pressure values that take into account the fill characteristics and slope of the embankment. The walls and slab designs were also checked using a three dimensional finite element model; however the results from that model were not considered to be reliable for the base slab as thin shell elements were used. The model was revised to represent the slab as beam elements in two orthogonal directions and the corresponding results compared relatively well with the conventional hand calculations.

A similar approach was used to model and design the transition structure between the inlet and the main culvert barrel. The transition structure at the inlet end of the culvert is 10 m long and has the same slab and wall thickness as the main culvert cross-section. The model used in the analysis is depicted in Figure 6.

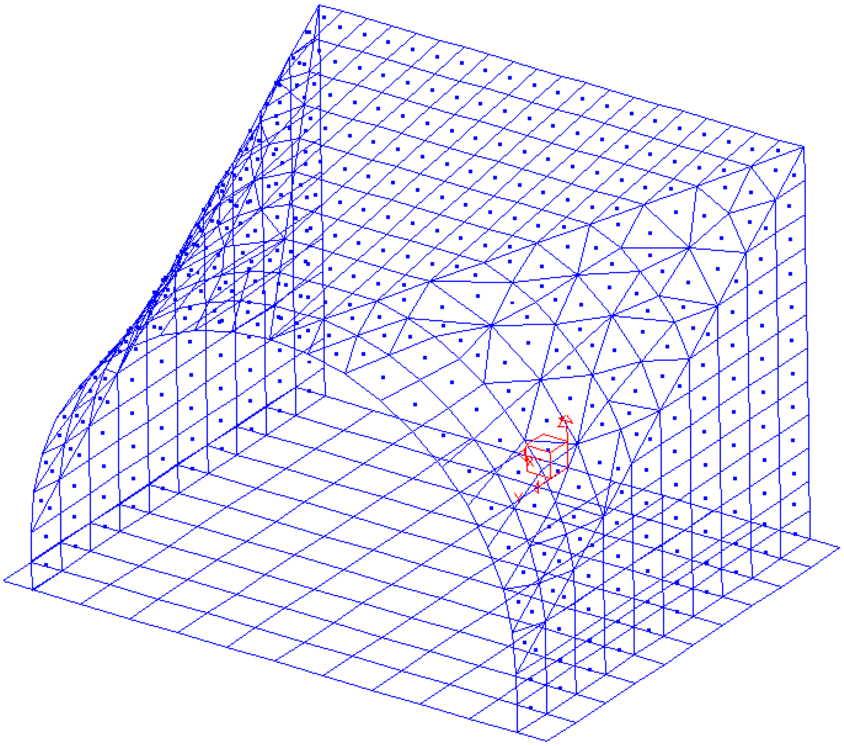


Figure 6: Computer Model for the Inlet Transition at Ksituan River

6.5 Culvert Barrel

The main cross-section of the culverts was required to support the highway loading and the varying fill embankment height along its length. Table 2 presents a summary of the culvert geometry and fill heights at both sites. As mentioned previously, the core of the embankment fill above the culvert was replaced with lightweight EPS to reduce the weight of the soil on the structure.

Table 2: Culvert Geometry and Embankment Fill Heights

	Ksituan River Culvert	Howard Creek Culvert
Inside diameter	11.0 m	10.0 m
Length	79.0 m	106.0 m
Maximum fill height	8.8 m	11.8 m
Maximum EPS thickness	4.2 m	5.2 m

Arching action was taken into account in calculations of the soil weight and earth pressure on the culvert. The structural analysis of the culvert cross section under different fill heights, utilized the following methods:

- Conventional methods based on beam theory with the culvert considered as supported on the base slab, which in turn was supported on vertical soil springs.
- Soil structure interaction finite element model using CANDE-CAD software. Figure 7 shows the model used in the analysis and Figure 8 shows the predicted deflected shape of the culvert.

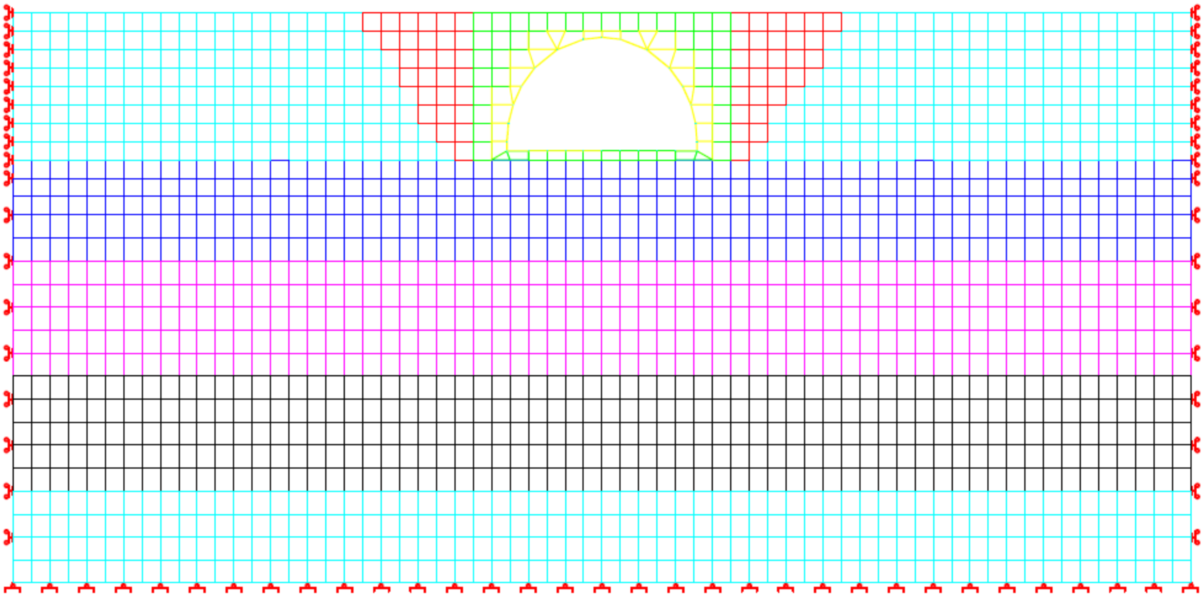


Figure 7: Computer Model for Soil Structure Interaction

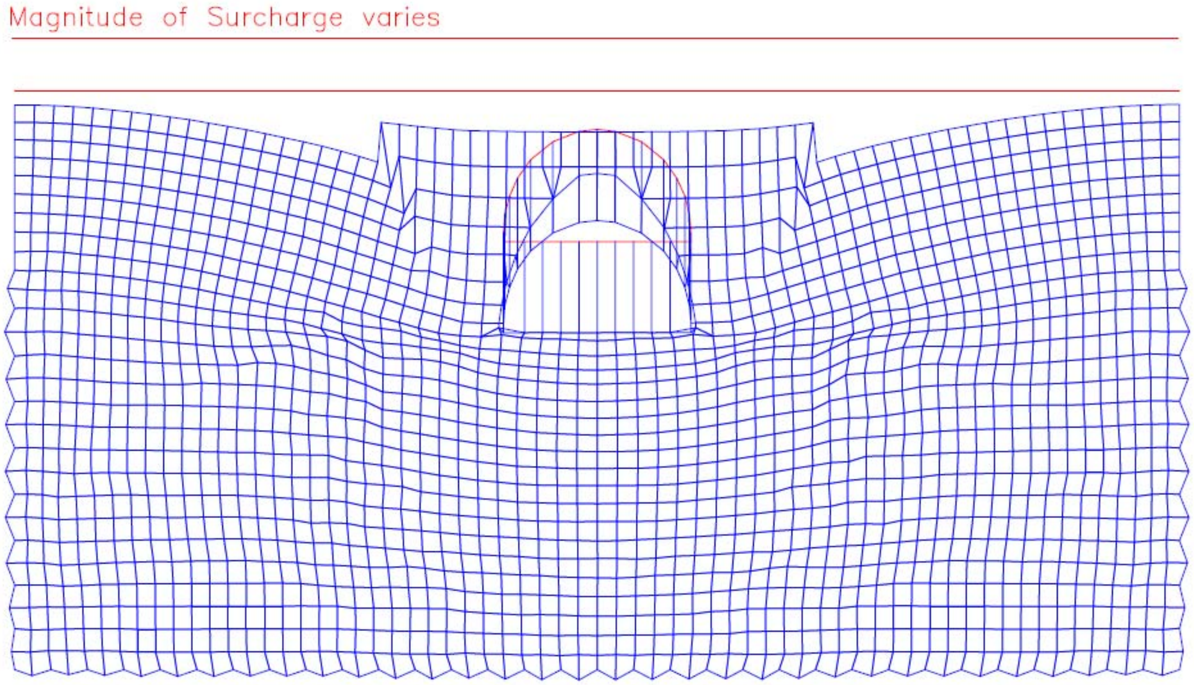


Figure 8: Predicted Deformed Shape

- Hybrid model that used the conventional model with additional springs attached to the culvert roof slab to capture the soil structure interaction behavior as shown in Figure 9. This method proved to produce comparable results to the CANDE-CAD model and was much simpler to apply and use. However the results were quite sensitive to the spring stiffness and a parametric study was carried out on the effect of such stiffness. Results of this work are not presented herein.

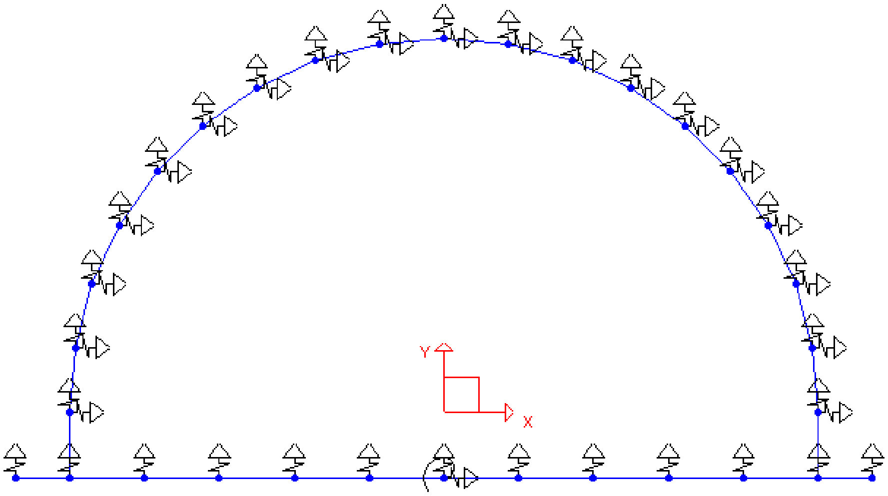


Figure 9: Hybrid Structural Model Idealizing Soil Interaction through Use of Springs

The result of using a variety of different methods to analyze the culvert cross-section was that an optimized and efficient design was achieved that would resist the loads imposed on it by the embankment fill above, and the settling subgrade below.

7. Construction Challenges and Innovations

The major challenges faced by the design team were not the only ones associated with the project. The sheer size and scale of the project was a challenge to the Contractor. In addition to the significant highway grading work on the project, the Contractor had to supply and place over 1,600,000 kg of reinforcing steel and 7,700 m^3 of concrete in roughly 8 months, primarily during the fall and winter, and in unstable valleys. Another 8,000 m^3 of EPS blocks had to be placed on top of the completed culvert structures during embankment fill construction. Innovative construction techniques had to be developed to complete the work on schedule.

Due to the unstable nature of the existing valleys, limits were placed on the size and proximity of excavations that could be open at the same time and the culverts had to be constructed in stages in order to maintain some support to the valley slide blocks. The Contractor constructed diversion pipes and cofferdams to handle water flow so that a shallow berm could be constructed in the river/creek bed to buttress the slopes. The culverts could then be constructed in 12 m long segments involving excavating, forming, pouring, and backfilling each segment before the next adjacent segment was started. The construction sequence at each site started with the centre segments of the culvert. After the centre two segments were completed and backfilled separately, the Contractor was permitted to work on two segments simultaneously at opposite ends of the culvert. Taking advantage of this, the Contractor staggered the use of the steel arch form such that both ends of each culvert could be built as quickly as possible. The base slab was constructed at one end of the culvert while the arch section was constructed at the opposite end. After the arch section was cast and sufficient curing time had elapsed, the forms were then moved to the recently completed base slab and the process repeated. Figure 7 shows the arch formwork and scaffolding being relocated and set up on a recently completed base slab. The last segments to be completed at each culvert were the inlet and outlet structures. Even with this sequential approach to construction limiting the size and number of open excavations, local slide movements exceeding 1 m per year were recorded.

Figure 10: Setting Steel Arch Formwork and Scaffolding on Completed Base Slab

As mentioned above, 7,700 m^3 of cast-in-place concrete had to be placed in roughly 8 months and the majority of the concrete work was scheduled to occur in the fall and winter. The size of the average concrete pour was 90 m^3 for the arch sections and 170 m^3 for the base slabs, and it was all supplied from a portable batch plant set up near the site.

At the peak of production, large concrete pours were occurring daily. To maintain this pace, the Contractor worked on both the Ksituan River and Howard Creek Culverts simultaneously, and utilized day and night reinforcing steel tying and placing crews. To further increase the speed of reinforcing steel placement, the cages within the arch section of the culverts were pre-tied off-site and lifted into place by crane. Despite losing close to four weeks of productive time due to extremely cold weather in December, the concrete work was completed in roughly eight months. Figure 8 shows the nearly completed Ksituan River culvert.

Figure 11: Nearly Completed Ksituan River Culvert

After the concrete culverts were completed and initial granular fill layer was placed, the EPS Geofoam had to be placed within the embankment fill. With 8,000 m^3 of EPS required for the project, the manufacturing of the material had to commence over 4 months in advance of the required date on site, and the material had to be stockpiled on site.

Although the low density of the EPS Geofoam made it an ideal lightweight fill material, its corresponding large volume made it very difficult to handle and manoeuvre. To minimize handling time, the Contractor developed an attachment for a wheel loader that could carry multiple blocks from the stockpile to their final placement location. Figure 9 shows the attachment which was an engineered rig mat with a railing system to secure the load. Able to carry 52 m^3 per load, this attachment helped the Contractor place the EPS Geofoam at a rate of up to 500 m^3 per day, placing all the required lightweight fill material in slightly over two weeks.

Figure 12: Wheel Loader with Attachment Transporting EPS Geofoam for Placement

8. Closure

The Highway 727 realignment project was completed in the fall of 2010 on time and on budget. The culverts at Ksituan River and Howard Creek are an excellent example of how innovative structural and geotechnical strategies can be combined to overcome the significant challenges associated with unstable river valleys. Using the culvert structure and embankment fills to buttress the valleys slopes, the shear piles to resist help soil pressure on the wingwalls, and lightweight EPS as fill material within the embankment resulted in a project that was constructible, cost effective, and will provide the local users with a safe and stable road alignment for years to come.

9. Acknowledgements

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