Project No.
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REDESIGN OF A FLOODING CULVERT FOR A HIGHWAY IN NORTHERN BC

(Weiser Concrete, 2020)

Prepared for:

______________, Industry Sponsor, ______________

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Prepared by:

____

Submitted on:

April 13, 2021

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DISCLAIMER

The work represented in this client report is the result of a student project at the British Columbia Institute of Technology. Any analysis or solution presented in this report must be reviewed by a professional engineer before implementation. While the student's performance in the completion of this report may have been reviewed by a faculty advisor, such review and any advice obtained therefrom does not constitute professional certification of the work. This report is made available without any representation as to its use in any particular situation and on the strict understanding that each reader accepts full liability for the application of its contents.

ACKNOWLEDGEMENTS

The following individuals deserve recognition for their help with this project:

- _______________, for providing the project scenario and for always being willing to answers my questions in detail
- Jan Bielenberg, for helping me to learn HEC-RAS and work through the challenging process of debugging model instability

April 13, 2021

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Industry Project Sponsor
____
______________, BC ______

Dear ____________

Submission of Final Report on Redesign of a Flooding Culvert for a Highway in Northern BC

I am submitting this report to outline my solution for redesigning a flooding culvert in Northern BC. The flooding culvert consisted of two, side-by-side corrugated metal pipe barrels. When the 0.5% AEP flood struck, the 1.8m diameter barrels did not have the capacity to pass $40m^3/s$ of flow, which caused the flood to overtop the road. You tasked me with redesigning the culvert so that flow does not overtop the road.

I have redesigned the culvert to consist of two, side-by side precast concrete box culverts, each with dimensions of 25m x 4m x 3m (L x W x H). This design passes the 0.5% AEP without causing water to overtop the road. The terrain modelling, hydraulic simulations, and design process were done using HEC-RAS 5.0.6. In total, this project took me 140 hours to complete.

While working on this project, I had the opportunity to teach myself how to use HEC-RAS, which was beneficial to my learning and enhanced my comprehension of how the program works. Furthermore, I found the project enjoyable and interesting to work on, which helped me to decide that I would like to focus on Water Resources as a Civil Engineering specialty. Thank you very much for sponsoring this project, meeting with me to answer questions, and for assisting me with my HEC-RAS modelling.

If you would like any additional information related to my project that is not included in this report, please contact me anytime at ______________ or ______________.

Sincerely,

____

cc: Jan Bielenberg, Faculty Advisor
Jacquie Russell, Communication Instructor

Attachment: Report

SUMMARY

Culvert X is located in Northern British Columbia, and allows Creek Y to pass underneath Highway Z. During flood events, Culvert X does not have the capacity to pass the peak flow and has caused water to backup and overtop the road. _______________, P.Eng, provided the project information for the purpose of an academic exercise. I created a model of Creek Y using HEC-RAS to design a new culvert that will pass the 0.5% AEP. Furthermore, I determined the flood construction level for a new house located 200m northwest of the culvert.

Culvert X is currently two side-by-side 1.8m diameter corrugated metal barrels. The inlet and outlet of the pipes are shaped to align with the sloping embankment of the highway. The culvert location is in mountainous terrain, with the typical land cover being forest and grass. The 0.5% AEP design flood (1 in 200-year flood) has a peak flow of 40 m^3/s.

The modelling for this project started on ArcGIS Pro & Civil 3D. _______________, P. Eng, provided me with Lidar data of the terrain as a Digital Terrain Model. I used ArcGIS Pro to georeference and visualize the creek bed and terrain in 3D. Next, I used Civil 3D to convert the DTM to a surface that I exported to HEC-RAS.

Once the terrain was in HEC-RAS I created a 1D model, a 1D/2D model, and a 2D model of the terrain. I then created Culvert X in each of the three models. The 1D model consists of a river reach with cross sections. The 1D/2D model has a river reach that is connected to 2D mesh in the floodplain area, over the right bank of Creek Y. The 1D and 2D areas are connected using a lateral structure with zero elevation so the natural riverbank acts as a levee. The 2D model is made of mesh that covers the entire floodplain and creek area.

When I ran the plan for the 1D/2D model it had the most accurate results. It displayed flow backing up at Culvert X and running down the road for approximately 50m, and then overtopping the road. Using the 2D model I was able to see the maximum flow in Culvert X was 16.581 m^3/s, which confirms that the culvert can not pass the 0.5% AEP of 40 m^3/s. Furthermore, the flood breaches the right overbank and rises to a maximum elevation of 619.2m at the location of the new house, 0.7m higher than the terrain elevation of 618.5m

For the new culvert design, I used the 1D/2D model to iterate a new culvert size and shape. It was the most accurate because I was able to define levees, ineffective flow areas, and see the profile view of the flood through the culvert. I designed a rectangular shaped culvert because the culvert can only be a maximum of 3m high to leave at least 1m of clearance to the road surface. A rectangular culvert allows the culvert to be wider than it is tall. I then used hand calculations to determine the minimum rectangular culvert width which was 7.4m with outlet control governing.

Using HEC-RAS I designed two side-by-side 25m x 4m x 3m (L x W x H) concrete box culverts. After adding this culvert design to my 1D/2D HEC-RAS model the culvert was able to pass the 0.5% AEP without causing the flood to overtop the road. HEC-RAS indicated that the flood in the culvert was entirely supercritical, indicating inlet control governed. I checked the design with hand calculations and discovered that the culvert is governed by inlet control. Furthermore, the flood does not reach the new house location, so the flood construction level is 618.5m, which is the natural terrain elevation.

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1.0 INTRODUCTION

In Northern British Columbia, Culvert X allows Creek Y to pass underneath Highway Z. During flood events, Culvert X does not have the capacity to pass floods beneath Highway Z and has caused water to overtop the road. ______________, P.Eng, is my industry sponsor for this project and has tasked me with redesigning the flooding culvert so that it does not cause flow to overtop the road. I was assigned this project for the purpose of an academic exercise.

I created a model of Creek Y on HEC-RAS to design a new culvert that will pass the 0.5% AEP. Furthermore, I determined the flood construction level for a new house located 200m northwest of the culvert. The flooding culvert consisted of two, side-by-side corrugated metal pipe barrels, as shown in Figure 1.

Figure 1*: Culvert X in Northern BC*[1] *(______________, 2020)*

Footnotes: [1] Image provided by sponsor, ______________, ______________

When the 0.5% AEP flood struck, the 1.8m diameter barrels did not have the capacity to pass $40m^3/s$ of flow, which caused the flood to travel down the side of the road and overtop the road about 50m to the right of the culvert.

The objectives for this project include

- creating a model of the flooding culvert in HEC-RAS and determining where the flood overtops the road
- iterating a new culvert size on HEC-RAS that will allow the flood to pass without overtopping the road

- determining the flood construction level for a new house being built 200m northwest of the culvert.

This project does not include an accurate 2D only model of the culvert. The model used for redesigning the culvert was a 1D/2D model as I found the results to be more accurate, and my sponsor indicated that a 1D/2D model is sufficient for the purposes of this project. The 1D/2D model is more accurate than the fully 2D model because I was able to define ineffective flow areas, levees, and see the results in profile view. A 2D model is included for the purpose of graphically understanding the maximum flow that can pass through the culvert, but the flooding scenario is not accurate.

The following information can be found in this report:

- Background information on the terrain, hydrology, and culvert
- Terrain modelling on ArcGIS Pro & Civil 3D
- Terrain and creek modelling in HEC-RAS
- Culvert modelling on HEC-RAS
- Results of culvert redesign on HEC-RAS
- Results of flood construction level analysis
- Hand calculations backing up HEC-RAS design

2.0 BACKGROUND

The background for this project consists of terrain information, local hydrology, and culvert details.

2.1 Terrain

This project is located in Northern British Columbia. The terrain is mountainous with elevations ranging from 598m to 778m. The landcover is typically forest and grass. Figure 2 shows an aerial photo of the terrain, with a blue dot representing the new house being built.

Figure 2: *Aerial photo of proposed house location in Northern BC[2] (_____, 2020)*

Footnotes: [2] Image provided by sponsor, _______________, _______________

The creek runs from the top to bottom of the aerial photo. There is a railway line downstream of the highway that will not have an impact on the site because the opening beneath the railway bridge is large enough to not constrict flow.

2.2 Hydrology

The normal flow in Creek Y is 1 m^3/s, with an approximate normal depth of 0.2m. The riverbed slope is 0.05 upstream of the culvert and 0.02 downstream of the culvert. The 0.5% AEP flood hydrograph is shown below in Figure 3.

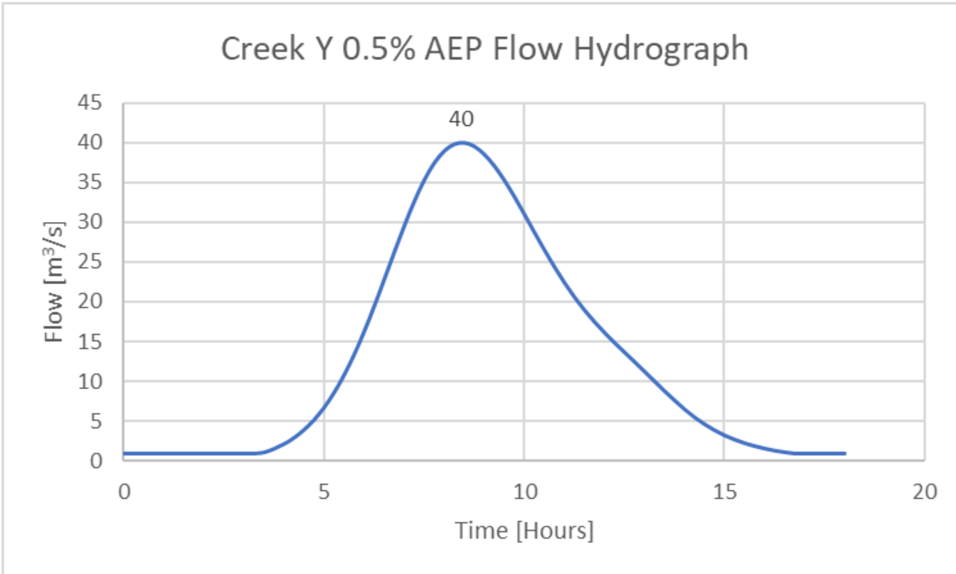

Figure 3*: 0.5% AEP Flow Hydrograph for Creek Y*

The maximum flow in Creek Y during the 0.5% AEP flood is 40 m^3/s, which occurs at approximately 8.5 hours into the flood.

2.3 Culvert X

The centreline of Highway Z crosses Creek Y at Station 135. The elevation of Highway Z is 618m at the point where Creek Y passes beneath it. The riverbed elevation is 613.6m directly upstream of Highway Z and 612.4m directly downstream. Culvert X consists of two 25m long identical culvert barrels side-by-side that allow Creek Y to pass underneath Highway Z. The two barrels are circular corrugated metal culverts with diameters of 1.8m each. The inlet and outlet of the pipe are mitered to conform with the sloping embankment of the highway.

During the 0.5% AEP which has a maximum flow of 40 m^3/s, the maximum flow through the culvert is 16.581 m^3/s, as displayed in Figure 4.

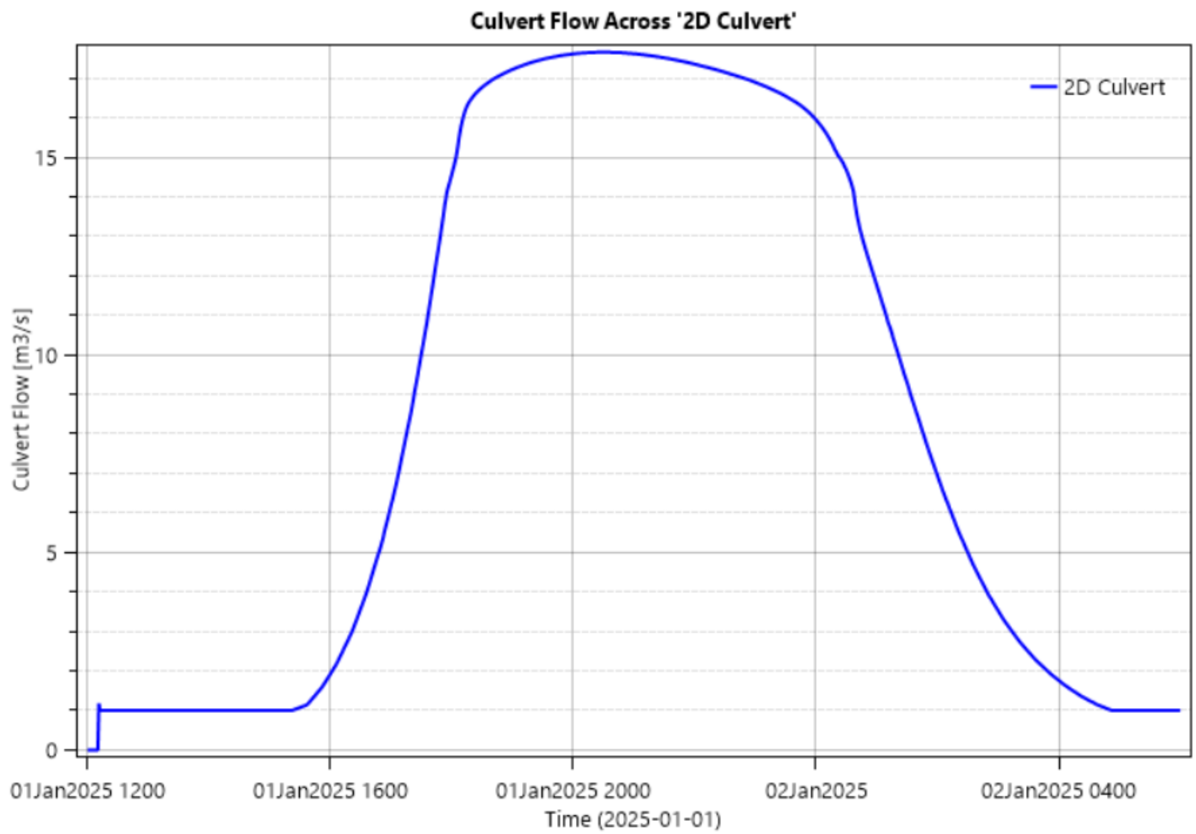

Figure 4: *Culvert flow*

The culvert flow hydrograph begins with a flow of 0 cms because HEC-RAS 2D simulations send flow through the creek starting at the top of the upstream reach.

3.0 HYDRAULIC MODELLING

The hydraulic modelling for this project consists of Terrain Modelling on ArcGIS Pro and Civil 3D, Terrain and Creek Modelling in HEC-RAS, and culvert modelling on HEC-RAS.

3.1 Terrain Modelling on ArcGIS Pro & Civil 3D

The hydraulic modelling for this project began on ArcGIS. Lidar data was provided by my sponsor in the form of a digital terrain model (DTM). I opened the DTM in ArcGIS Pro and georeferenced it to ensure that it opened in the correct location. I then draped an aerial photo on top of the terrain and viewed the terrain in 3D to ensure that the creek bed was properly defined in the DTM. Once I visualized the DTM in 3D, I opened it in Civil3D. On Civil3D I converted the DTM into a surface. The surface was then exported as a terrain so that it could be used in HEC-RAS.

After exporting the surface as a terrain, I created a landcover map on Civil3D for use in HEC-RAS 2D modelling. The manning's n values in Table 1 (USACE, 2010) are a legend for the land cover map created in Civil3D shown in Figure 5.

***Table 1**: Land Cover Map Legend*

Colour	Land Cover	Manning's n Value
Black	Buildings	1
Tan	Dirt	0.03
Brown	Dirt Roads	0.03
Dark green	Forest	0.07
Bright green	Grass with Trees	0.035
Yellow	Grass	0.03
Light blue	Creek	0.045
Light grey	Paved Road	0.016

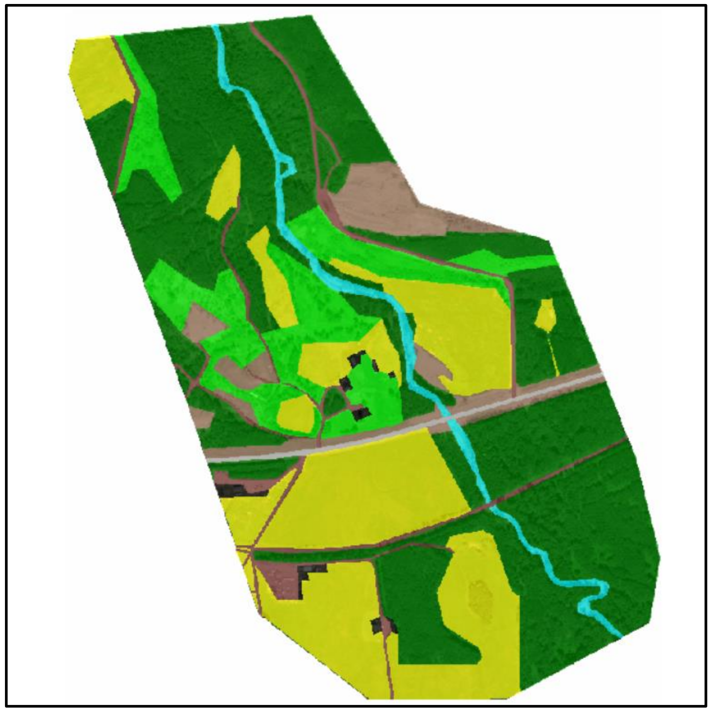

***Figure 5**: Land Cover Map*

After creating the landcover map I exported it as a shapefile of polygons into HEC-RAS. The shapefile was georeferenced directly on top of the terrain, so when I opened it in HEC-RAS, the program defined the manning's N values on the terrain by their corresponding values from the shapefile

3.2 Terrain and Creek Modelling in HEC-RAS

For the purposes of this report, Creek Y represents a 660m long stretch of river as shown in Figure 6.

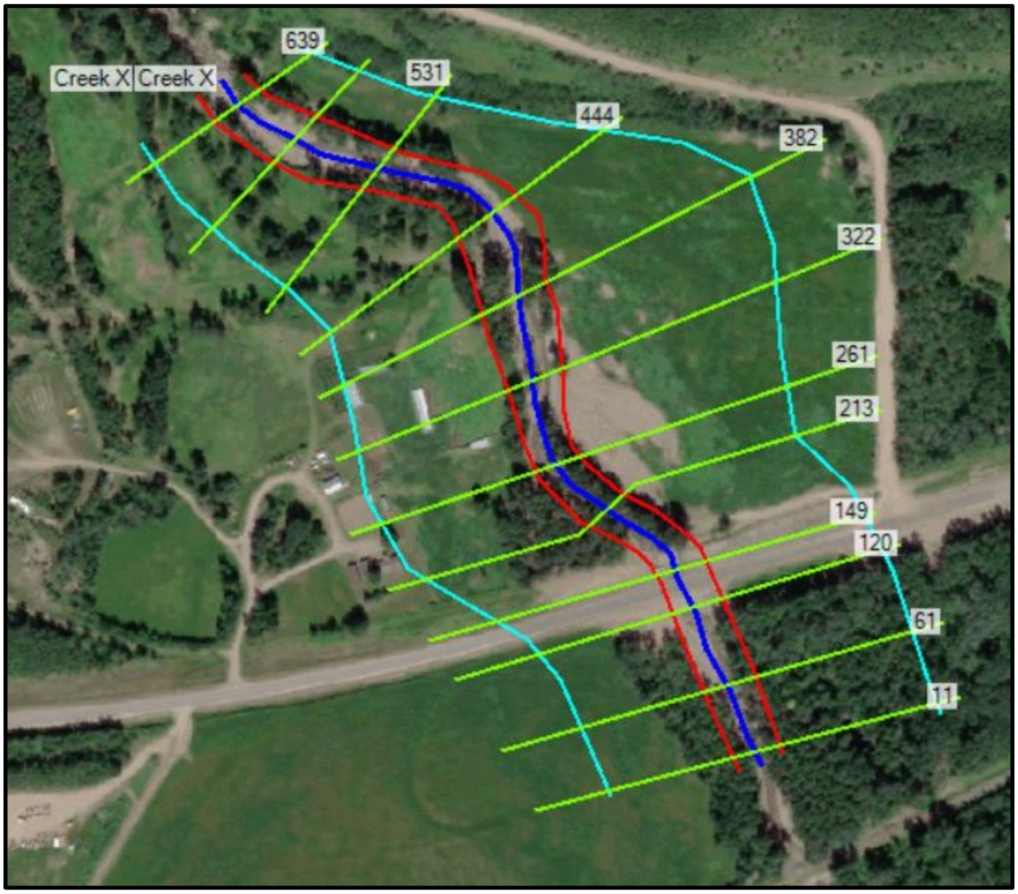

***Figure 6**: Creek Y 1D river reach*

The centreline starts upstream with an elevation of 623m at Station 660 and ends downstream with an elevation of 610m at Station 0. The entire river in the DTM was not modelled because upstream of station 660 the river has a steep slope which will cause fast flow and create an unsteady hydraulic model (Goodell, 2010). At station 660 the flow has returned to steady speed. Furthermore, downstream of the culvert there is a railway crossing that does not affect the culvert because the opening beneath the railway crossing is large enough that it does not constrict flow.

Once the terrain was in HEC-RAS a 1D model of the river reach was created. The 1D model included the river centreline, bank lines, cross sections, and flow paths. The existing culvert structure was created in 1D by adding a roadway structure with elevation equal to the terrain elevation in the terrain model.

Next a 1D/2D model was created by defining 2D mesh in the floodplain area but keeping the river reach 1D. The 1D river reach was connected to the 2D floodplain using a lateral structure with zero elevation to allow the natural riverbank to act as a levee. The culvert remained in the model from the first 1D model. The 1D/2D model is the model that was used for accurately redesigning the culvert, and it is shown in Figure 7.

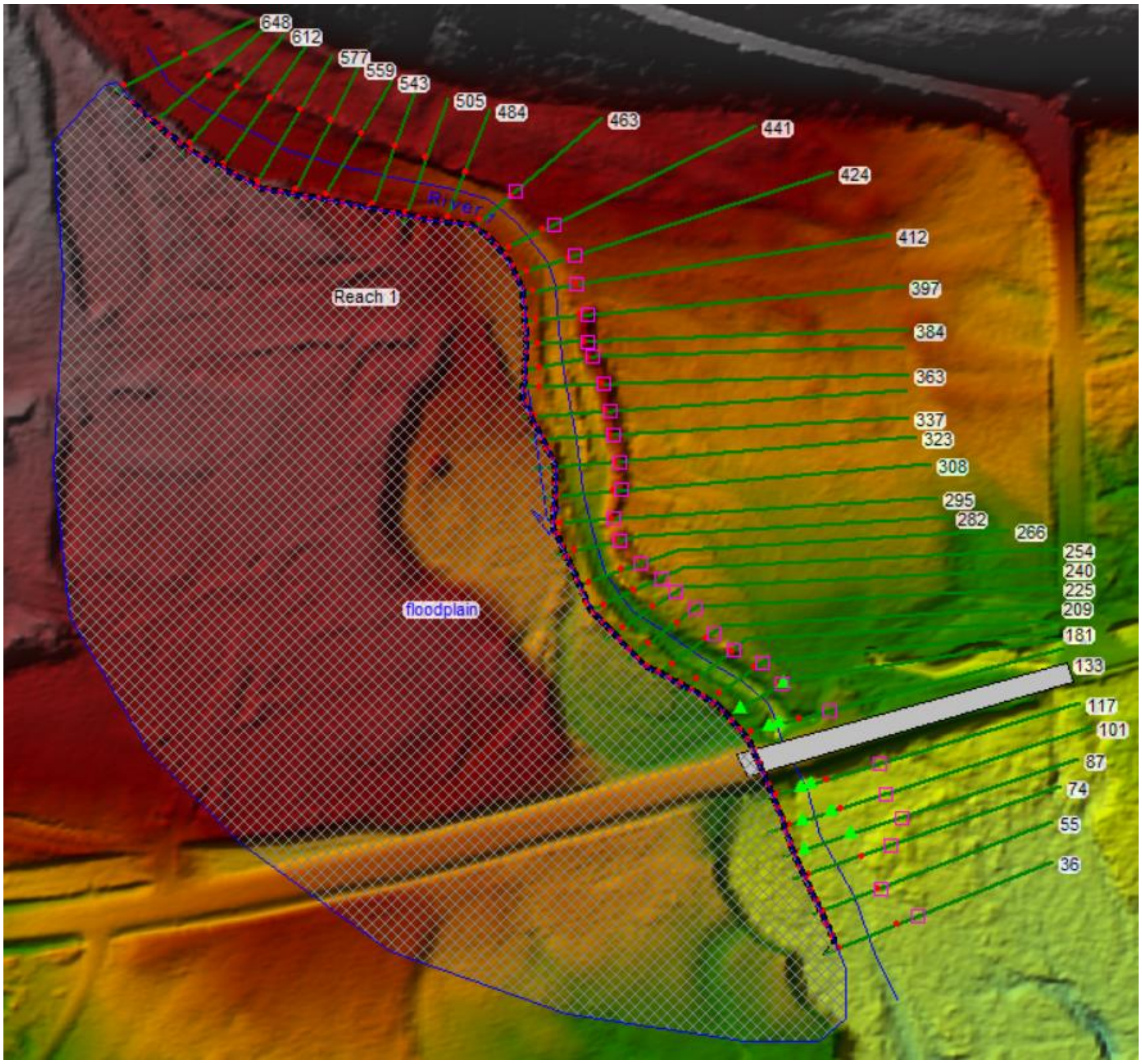

***Figure 7**: 1D/2D model of Creek Y*

The green triangles represent the ineffective flow areas, drawn at a 1:1 ratio upstream of the culvert and a 2:1 ratio downstream of the culvert (USACE, n.d.). The pink squares represent the high points on the terrain river banks that act as a levee for flow. These points are useful because HEC-RAS only adds flow to the right of the points if the flow in the river becomes higher than those points (Maeder, n.d.). Lastly, the long grey rectangle at station 133 represents Highway Z.

Finally, I created a 2D only model as shown in Figure 8.

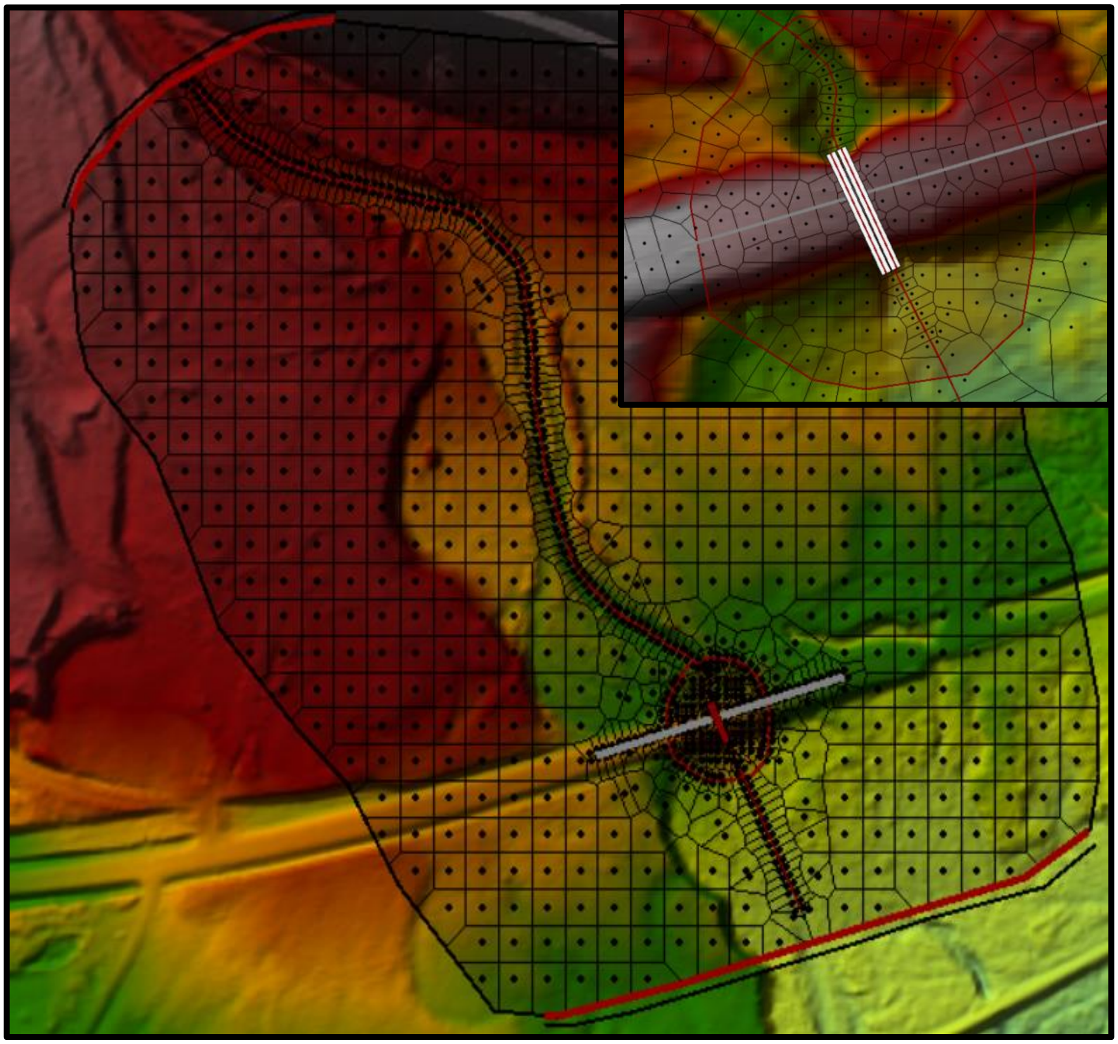

***Figure 8**: 2D only model of Creek Y and Zoomed in 2D Model of Culvert X (top right)*

The 2D model was created by defining 2D mesh in the entire floodplain and river area. I put breaklines at the location of the river and culverts to ensure that the elevation points in the 2D mesh aligned with the centreline of the river and culvert.

3.3 Culvert Modelling on HEC-RAS

The HEC-RAS culvert input parameters were determined using the HEC-RAS Hydraulic Reference Manual (US Army Corps of Engineers, 2010). The input parameters are shown in Figure 9 below.

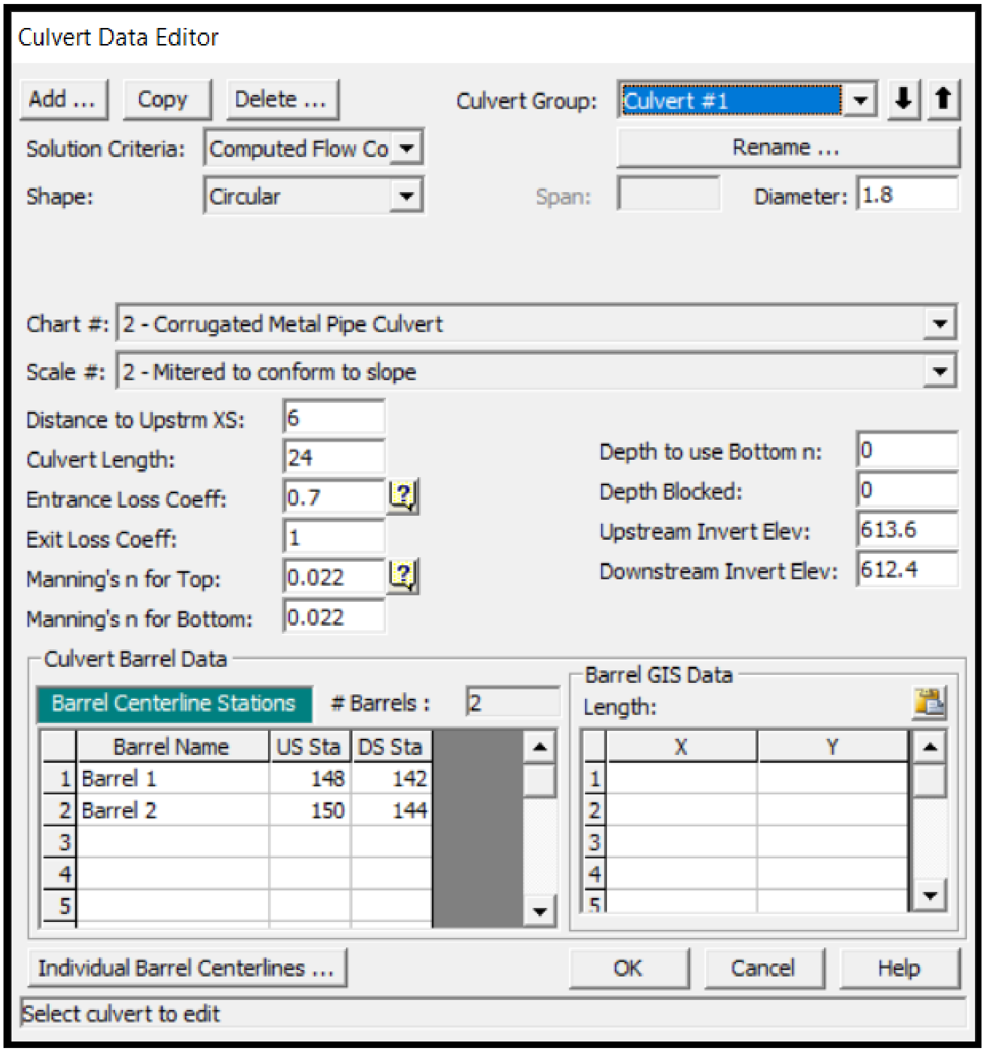

***Figure 9**: Culvert input parameters*

The entrance loss coefficient was taken as 0.7 (Page 189) for corrugated metal pipes mitered to conform to fill slopes. The exit loss coefficient was taken as 1.0 to account for an abrupt expansion of flow, which is common in culverts (Page 190). The manning's n for the top and bottom was taken to be 0.022 for Helical 72 inch (1.8m) corrugated metal pipe (Page 188). Lastly, the upstream invert elevation was equal to the upstream riverbed elevation, which is 613.6m. The downstream invert elevation is also equal to the downstream riverbed elevation, which is 612.4m

4.0 CULVERT DESIGN AND FLOOD RESULTS

The results of running the plan with the original 1.8m diameter culverts are shown in Figure 10.

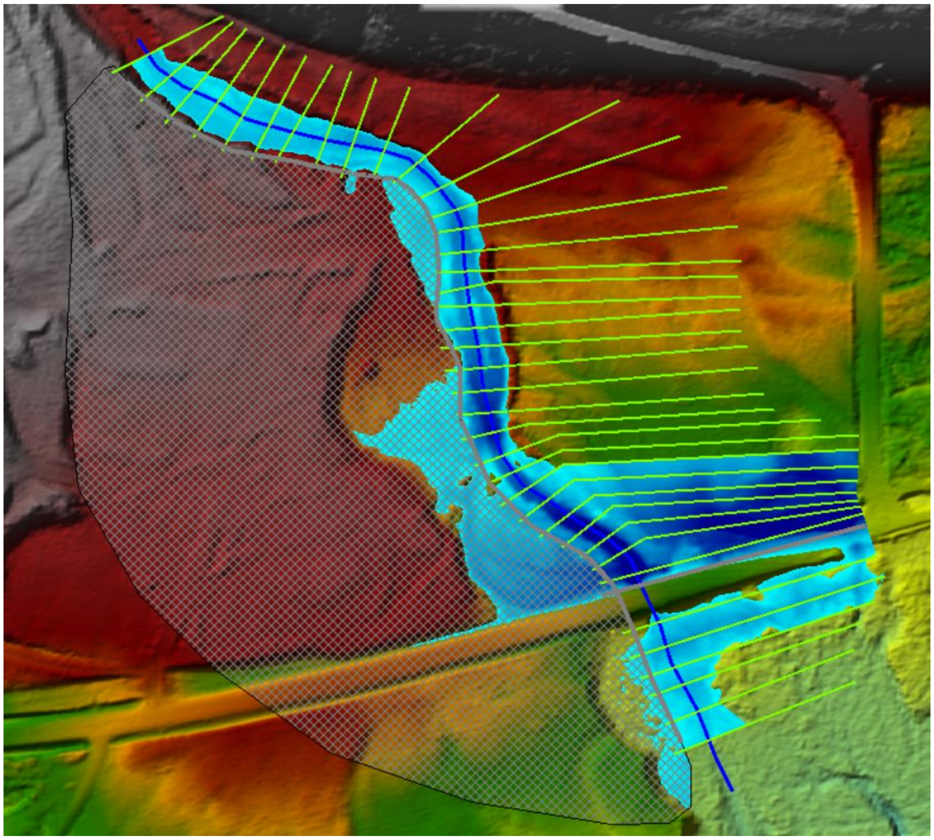

***Figure 10**: Maximum flood depth in Creek Y with Original Flooding Culvert X*

The flooding shown above is the maximum flood depth that occurs during the 0.5% AEP which results in 40m^3/s of flow. The flow is backed up at the culvert and travels down the side of the road for about 50m until it overtops the road.

In order to prevent the flood overtopping the road, I sized a new culvert so that it could pass the 0.5% AEP, which was an iterative process. The culvert entrance invert elevation on the riverbed is 613.6m, and the roadway elevation overtop of the culvert is 617.8m. The distance between the road surface and the top of the culvert must be at least 1m, therefore the maximum height of the culvert is shown in the calculation below:

$$617.8\text{m} - 1\text{m} - 613.6\text{m} = 3.2\text{m}$$

Therefore, the maximum height of the culvert is 3.2m, however I decided to design the culvert to be a maximum height of 3m to accommodate precast culvert sizing. I began the design process by increasing the diameter of the two circular pipe culverts to equal 3m. However, after running the simulation, the culverts were still not large enough and caused flow to overtop the road. This indicated that a circular culvert shape can not be used because there is not enough clearance from the riverbed to the roadway surface for a culvert larger than 3m high.

I then decided to design a rectangular culvert because the height can be 3m and the width can be wider than 3m. Using a trial-and-error method on HEC-RAS to design the optimum culvert width would be tedious, so I used hand calculations to determine the minimum culvert width. The equations I used came from *Fundamentals of Hydraulic Engineering Systems* (Houghtalen, Akan, Hwang, 2015). See Appendix A for the hand calculations supporting the minimum culvert width.

Based on my hand calculations in Appendix A, the culvert will operate under outlet control and will require a minimum width of 7.4m to pass the design flood of 40m^3/s. I used HEC-RAS to design the culvert as two side-by-side precast concrete box culverts. Each precast concrete box culvert has dimensions of 3m high by 4m wide, which satisfies the minimum width requirement of 7.4m.

I decided to design my culverts to have a total width of 8m, rather than the minimum of 7.4m, for practicality purposes because the culvert will be a precast concrete box that comes in standard sizes. Furthermore, I decided to split the 8m wide culvert into two 4m wide culverts because an 8m wide and 3m tall single culvert would be instable without a support in the middle.

After designing my culvert on HEC-RAS, I adjusted the ineffective flow areas to accommodate the new entrance size, as well as adjusted the cross section spacing. When I ran my model, there were no errors while running the plan. An image of the maximum flow depth during the 0.5% AEP is shown in Figure 11.

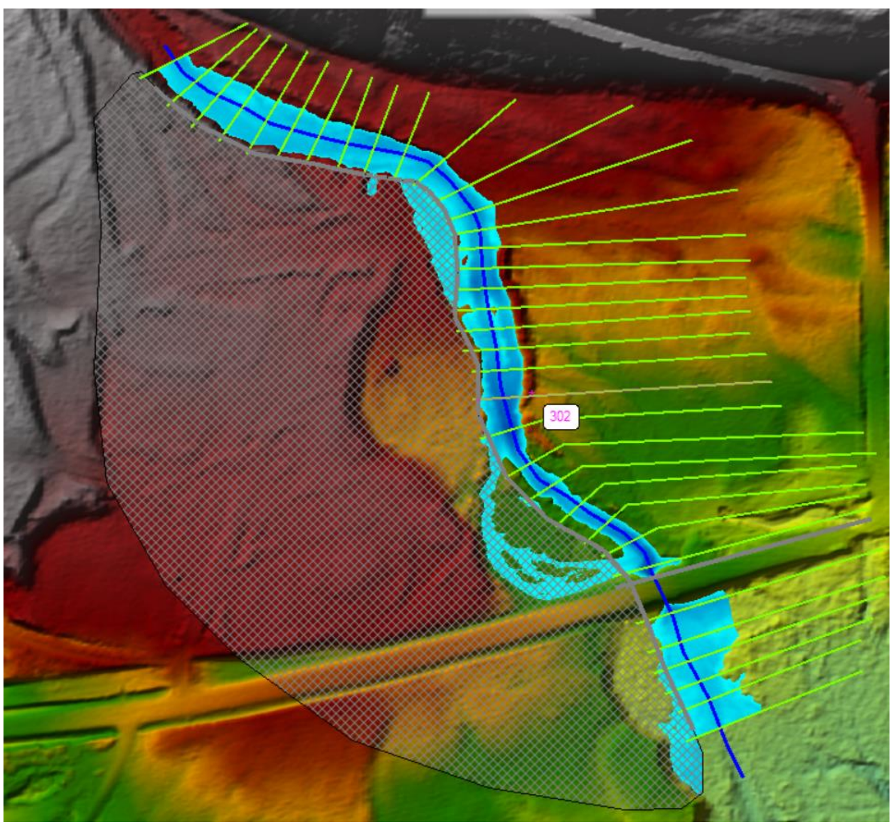

***Figure 11**: Maximum flood depth in Creek Y with newly designed culverts*

The new culvert can pass the 0.5% AEP without causing water to overtop the road. Furthermore, the energy grade line did not spike at any location and stayed at a steady downhill slope indicating a stable model.

After the model was finished running there were three different warnings that could be a cause for concern under the "summary of errors, warnings, and notes" button. Those three errors were:

1. The Velocity head has changed by more than (0.15m). This may indicate the need for additional cross sections.
2. The conveyance ratio is less than 0.7m or greater than 1.4. This may indicate the need for additional cross sections.
3. The energy loss was greater than (0.3m) between the current and previous cross section. This may indicate the need for additional cross sections.

After seeing these errors, I attempted to add additional cross sections but as soon as I ran the plan there were hundreds of errors and the plan would crash. I believe that the cross section spacing that I have in my 1D/2D model is the optimum spacing, and the reason these errors are showing up is because the bathymetry of the cross sections differs greatly throughout the river. Creek Y naturally has a rocky bottom with locations of split flow, large obstructions, and non uniform side slopes. For this reason, I decided that I would ignore the warnings.

The HEC-RAS model indicated that the flow in the culvert was entirely supercritical. This would mean that the culvert is operating under inlet control conditions, however when I sized the culvert using hand calculations, I found that outlet control governed. The reason for this discrepancy is that outlet control governed with a culvert that is 7.4m wide. When I designed my culvert in HEC-RAS it had a total width of 8m. The additional 0.6m of width caused the culvert to switch from outlet to inlet control.

To ensure that the HEC-RAS model was running properly, and that inlet control indeed governs, I used hand calculations to compare the maximum flow in the culvert based on inlet control and outlet control. Based on my hand calculations I found that less flow can pass into the barrel than the amount of flow that can pass through the barrel, indicating that inlet control governs. This confirms that the HEC-RAS model is running properly and that the flow in the culvert is entirely supercritical. See Appendix B for the hand calculations confirming that inlet control governs with an 8m wide culvert.

4.1 Flood Construction level Results

The new house is being built about 200m northwest of the culvert. In the 1D/2D model with the flooding Culvert X, the water breaches the right overbank and rises to a maximum elevation of 619.2m at the location of the new house, 0.7m higher than the terrain elevation of 618.5m. The flood construction level would be 1m higher than the maximum water elevation, so therefore the flood construction level would be 620.2m, or 1.7m higher than the terrain elevation.

After designing the new concrete box culvert, the flood does not reach the new house location. Therefore, if the new culvert design is constructed the flood construction level for the new house is 618.5m, which is the natural terrain elevation.

5.0 CONCLUSION

Culvert X consists of two 1.8m diameter corrugated steel culvert barrels in Northern BC. Culvert X currently does not have the capacity to pass the 0.5% AEP of 40 m^3/s and causes flow to overtop the road. I have designed a new culvert that is able to pass the 0.5% AEP without causing water to overtop the road or significantly flood the surrounding area.

I began by converting lidar terrain data to a HEC-RAS terrain using Civil3D. Then I created a 1D only, 1D/2D, and 2D only model of the flooding culvert. I decided to use the 1D/2D model to design the new culvert because it had the most accurate results. The results were the most accurate because I was able to define ineffective flow areas, levees, and see the profile view of the flood through the culvert. To design the new culvert I used hand calculations (see Appendix A) to find the minimum culvert size.

The new culvert I designed consists of two side-by-side precast concrete box culverts, each with dimensions of 25m x 4m x 3m (L x W x H). I chose to use a rectangular shape because the maximum height that the culvert can span while leaving at least 1m clearance with the roadway is 3m. Using a rectangular shape allows the width to be greater than the height which results in a higher capacity. After running the HEC-RAS model, the new culvert did not cause flow to overtop the road.

Prior to designing the new culvert, the flooding of Culvert X caused water to overtop the right overbank and rise to an elevation of 619.2m at the location of the new house. Therefore, prior to designing the new culvert the flood construction level would be 620.2m. After designing the new concrete box culvert, the flood does not reach the new house location, and the flood construction level would be the terrain elevation of 618.5m.

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Appendix A: Culvert Sizing Hand Calculations

Maximum available headwater flow depth, H, should be 0.5m below the roadway elevation to prevent roadway flooding.

Roadway elevation above culvert = 617.8m

* Culvert entrance invert elevation is equal to the riverbed elevation at the culvert entrance.

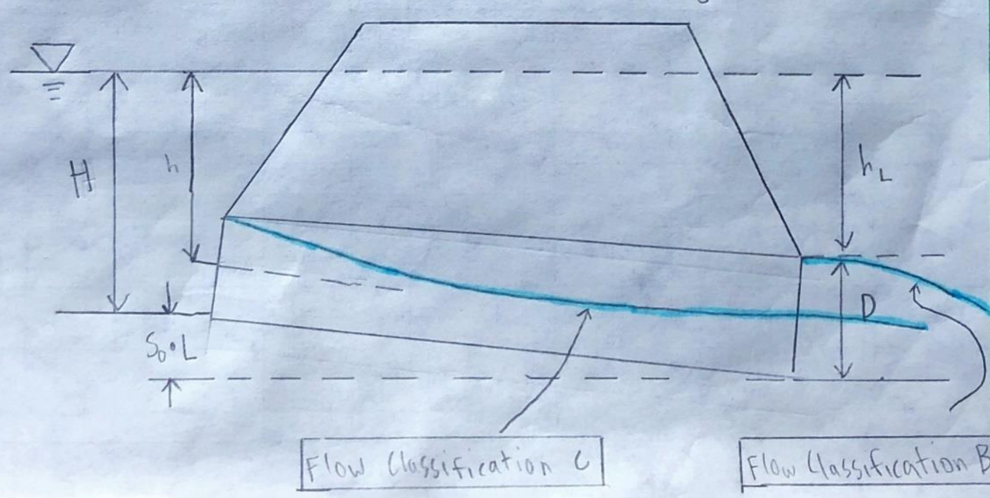
Culvert entrance invert elevation = 613.6m

$\therefore \quad H = 617.8m - 0.5m - 613.6m$

$H = 3.7m$

The culvert will be sized base on flow classifications b) and c) as shown in the diagram below:

Flow classification B) and C) diagram, from 'Hydraulic Engineering Systems 4th edition' by Robert J. Houghtalen, A. Osman Akan, and Ned H.C. Hwang



Culvert Sizing	CIVL 4090 Trevor Thiessen	2021-03-18	2/5

Assuming Full pipe flow or flow classification B), the energy balance can be expressed as:

$$H + S_0 L = D + h_L$$

$$h_L = H + S_0 L - D \quad (1)$$

The length, L, of culvert is 24 m and the slope, S_0, is equal to:

$$S_0 = \frac{\text{Upstream invert elev.} - \text{Downstream invert elev.}}{L}$$

$$S_0 = \frac{613.6\,m - 612.4\,m}{24\,m} = 0.05$$

The distance between the road surface and the top of the culvert must be at least 1m, therefore the maximum depth (height), D, of the culvert is:

$$D = 617.8\,m - 1\,m - 613.6\,m$$

$$D = 3.2\,m$$

However, a depth of 3m will be used because the culvert shape needs to be a precast concrete rectangle. This is because the culvert cannot be circular in shape because the max circular shape is 3.2 m diameter which will not pass the design flood of 40 m^3/s. Due to this, the culvert must be wider than it is tall, and therefore a precast concrete rectangle is a good option.

Plugging variable into equation ① results in: a head loss, h_L, of:

$$h_L = H + S_o \cdot L - D \qquad \text{(Eqn 1)}$$

$$= 3.7m + (0.05)(24m) - 3m$$

$$h_L = 1.9m$$

Equate $h_L = 1.9m$ to headloss Eqn from:

'Hydraulic Engineering Systems 4th Edition' by Robert J. Houghtalen, A. Osman Akan, and Ned H.C. Hwang

$$h_L = k_e\left(\frac{V^2}{2g}\right) + \frac{n^2 V^2 L}{R_h^{4/3}} + \frac{V^2}{2g} \qquad \text{(Eqn 8.17b)}$$

where k_e = entrance loss coefficient
n = manning's n value
R_h = hydraulic radius
V = velocity
g = gravity
L = length of culvert

$k_e = 0.5$ (HEC-RAS Hydraulic Reference manual version 5.0 Table 6-4)

for square edged reinforced concrete box culvert

$n = 0.012$ (HEC-RAS Hydraulic reference manual version 5.0 Table 6-1)

for concrete culvert, straight and free of debris

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$R_H = \frac{A}{P}$ where A = area
P = wetted perimeter

$$R_H = \frac{W \times D}{2W + 2D} = \frac{3W}{2W + 2(3)} = \frac{3W}{2(W+3)} = \frac{1.5W}{W+3}$$

$V = \frac{Q}{A}$ where Q = flow

$$v = \frac{Q}{W \times D} \quad \frac{40\,m^3/s}{W \times 3m} = \frac{13.33}{W}$$

$g = 9.81\,m/s^2$ and $L = 24\,m$

$$h_L = k_e\left(\frac{v^2}{2g}\right) + \frac{n^2 v^2 L}{R_h^{4/3}} + \frac{v^2}{2g}$$

$$h_L = 1.9\,m = 0.5\left(\frac{\left(\frac{13.33}{W}\right)^2}{2 \times 9.81}\right) + \frac{0.012^2\left(\frac{13.33}{W}\right)^2 \times 24}{\left(\frac{1.5W}{W+3}\right)^{4/3}} + \frac{\left(\frac{13.33}{W}\right)^2}{2 \times 9.81}$$

$$1.9 = \frac{4.528}{W} + \frac{0.358/W}{\frac{W^{4/3}}{(W+3)^{4/3}}} + \frac{9.057}{W}$$

$$1.9 = \frac{13.585}{W} + \frac{0.358(W+3)^{4/3}}{W^{7/3}}$$

$$1.9 = \frac{13.585\,W^{4/3}}{W^{7/3}} + \frac{0.358(W+3)^{4/3}}{W^{7/3}}$$

$$1.9 = \frac{13.585\,W^{4/3} + 0.358(W+3)^{4/3}}{W^{7/3}}$$

Solved numerically on excel:

$\boxed{W = 7.4\,m}$

Assuming partially full pipe flow or flow classification ( ), the head (h) is measured above the centreline of the pipe and can be expressed as:

$$h + \frac{D}{2} = H = 3.2$$

$$h = 3.2 - \frac{D}{2} = 3.2 - \frac{3}{2} = 1.7$$

Substitute this equation for h into flow equation for orifice flow from:

'Hydraulic Engineering Systems 4th Edition'

by Robert J. Houghtalen, A. Osman Akan, and Ned H. C. Hwang

$$Q = C_d A \sqrt{2gh} \qquad \text{(Eqn 8.19)}$$

where C_d = coeffecient of discharge

A = cross sectional culvert area

h = head

$C_d = 0.60$ for square edged entrance

$A = W \times D = 3W$

$$Q = 0.60\,(3W)\,\sqrt{2(9.81)\,(1.7)}$$

$$40 = 10.396\,W$$

$$\boxed{W = 3.9\,m}$$

The culvert will operate under outlet control and will require 3m x 7.3m (HxW) minumum dimensions.

Appendix B: Culvert Supercritical Flow Check

* According to my hand calculations it was found that the culvert will operate under outlet control if it is designed with the minimum dimensions of 3m x 7.3m (H x W).

- However, the culvert will be designed to fit standard precast concrete box culvert specifications. Therefore, two side-by-side 3m x 4m (H x W) concrete box culverts were designed on hec-ras

- Hec-RAS has calculated that the two 3m x 4m culverts have entirely supercritical flow, indicating that inlet control governs. The following calculations will check to see if inlet control governs with this culvert design:

Assuming partially full pipe flow or flow classification (), the head (H) is measured above the centreline of the pipe and can be expressed as:

$$h + \frac{D}{2} = H = 3.2$$

$$h = 3.2 - \frac{D}{2} = 3.2 - \frac{3}{2} = 1.7$$

Substitute this equation for h into flow equation for orifice flow from:

'Hydraulic Engineering Systems 4th Edition'
by Robert J. Houghtalen, A. Osman Akan, and Ned H. C. Hwang

$Q = C_d A \sqrt{2gh}$ (Eqn 8.19)

where C_d = coefficient of discharge
A = cross sectional culvert area
h = head

$C_d = 0.60$ for square edge entrance

$A = 3m \times 4m = 12 m$

$Q = 0.60 (12 m) \sqrt{2 \times 9.81 \times 1.7}$

$Q = 41.58 \frac{m^3}{s} \times 2$ barrels $= 83.16 m^3/s$

The flow for inlet control is $83.16 m^3/s$

Now, Assuming Full pipe flow or Flow classification B):

The head loss (h_L) was previously calculated to be 1.9 m on page 3 (Eqn 1).

Equate the $h_L = 1.9$ m to head loss Eqn from:

"Hydraulic Engineering Systems 4th Edition"
by Robert J. Houghtalen, A. Osman Akan, and Ned H. C. Hwang

$h_L = K_e \left(\frac{V^2}{2g}\right) + \frac{n^2 V^2 L}{R_h^{4/3}} + \frac{V^2}{2g}$ (Eqn 8.17b)

Where: K_e = entrance loss coefficient

n = manning's n value

R_h = hydraulic Radius

V = velocity

g = gravity

L = length of Culvert

$K_e = 0.5$ (hec ras hydraulic Reference Manual version 5.0 table 6-4)

$n = 0.012$ (HEC-RAS hydraulic reference manual version 5.0 table 6-1) (for concrete culvert, straight, free of debris)

$R_H = \frac{A}{P}$ where A = area

P = wetted perimeter

$$R_H = \frac{W \times D}{2W + 2D} = \frac{4 \times 3}{2 \times 4 + 2 \times 3} = 0.857 \text{ m}$$

$g = 9.81 \frac{m}{s^2}$ and $L = 24$ m

$V = \frac{Q}{A}$ where Q = Flow

A = area

$$V = \frac{Q}{3 \times 4} = \frac{Q}{12}$$

$$h_L = K_e\left(\frac{V^2}{2g}\right) + \frac{n^2 V^2 L}{R_h^{4/3}} + \frac{V^2}{2g}$$

$$h_L = V^2\left[\frac{K_e}{2g} + \frac{n^2 L}{R_h^{4/3}} + \frac{1}{2g}\right]$$

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$$V^2 = \left(\frac{Q}{12}\right)^2 = \frac{Q^2}{144} = \frac{h_L}{\left[\frac{Ke}{2g} + \frac{n^2 L}{Rh^{4/3}} + \frac{1}{2g}\right]}$$

$$Q = \sqrt{\frac{144\ h_L}{\left[\frac{Ke}{2g} + \frac{n^2 L}{Rh^{4/3}} + \frac{1}{2g}\right]}}$$

$$Q = \sqrt{\frac{144\ (1.9)}{\left(\frac{0.5}{2\times 9.81} + \frac{0.012^2 \times 24}{(0.857)^{4/3}} + \frac{1}{2\times 9.81}\right)}}$$

$$Q = 58.227\ \frac{m^3}{s} \times 2 = 116.45\ \frac{m^3}{s}$$

$116.5\ \frac{m^3}{s}$ flow can pass through the barrel. $83.2\ \frac{m^3}{s}$ of flow can pass into the barrel.

∴ Therefore inlet control governs and the Flow is supercritical