V–04.01 General

This Section is intended to provide a guide for the sizing of pipe culverts to convey a design discharge of less than approximately 500 cubic feet per second (cfs).

A hydraulic report is generally not required to document the size selection for pipe culvert crossings. However, the hydrology, hydraulics and culvert modeling data shall be retained in the project files. Example hydrologic and hydraulic data for a pipe culvert crossing are provided in Appendix V-04 A.

The function of a culvert is to convey surface water discharges through a highway, or through an approach roadway. In addition to this hydraulic function, a culvert must also be able to withstand construction and highway loads passing over it. This Section only addresses hydrology and hydraulics for these crossings. Structural features, culvert selection criteria, and culvert height of fill data are provided on the Standard Drawings, in Section V-05 and in Appendix V-05 A of the Design Manual, respectively.

The designer should consult AASHTO'S, "Highway Drainage Guidelines" as a reference.

V–04.02 General Policies

The following general policies apply to the sizing of culvert crossings:

1. The minimum diameter of new centerline pipe culverts shall be 24 in. The maximum length of this diameter culvert shall be 100 feet (measured by pay length, from opening of end section to opening of end section at the crown of the pipe) for new installations. If more length is needed, a 30 in. diameter culvert should be used. Existing culverts smaller than 30" in diameter may be extended to lengths greater than 100 feet.

2. The minimum diameter for approach culverts up to 75 feet in length shall be 18 inches. Approach culverts longer than 75 feet shall have a minimum diameter of 24 inches.

3. Culvert material types for centerline and approach culverts shall be in accordance with the requirements of Section V-05 of the Design Manual. Both smooth-walled and corrugated culvert types shall be modeled.

4. New centerline culvert crossings should first be modeled using a smooth-walled (such as RCP or spiral rib corrugated) culvert (Mannings's n = .012). Next, the crossing should be modeled using corrugated pipe (Manning's n=.024), and the diameter shall be adjusted as necessary such that a design headwater is provided which is either lower than that provided by the smooth-walled pipe type, or no greater than 2% higher than the headwater provided by the smooth-walled pipe. Most often, increasing the diameter of the corrugated alternative by one size (6 inches) is sufficient to satisfy these requirements.

For new centerline culvert installations, only hydraulic design data for the smooth-walled culvert types shall be shown in Section 50 of the plans. For any culvert which needs to be extended and also is categorized by Article 89-14 as requiring analysis and sizing, the hydraulic data for the proposed culvert extension shall be shown in Section 50 of the plans.

5. When approach culverts for private drives, field drives or township roads are sized, the corrugated alternative shall be hydraulically sized first, and if the corrugated alternative size is 24" diameter or less, then the smooth-walled alternative shall be specified in the same (either 18" or 24") diameter. When the corrugated pipe size has been determined to be 30" or larger, then the smooth-walled alternative size shall be determined by modeling, and a smooth-walled alternative size shall be selected which provides a headwater sufficiently equivalent to that of the corrugated alternative. A smooth-walled approach culvert alternative shall be considered sufficiently equivalent when the headwater is either lower than, or up to 2% higher than the headwater provided by the corrugated alternative. Further discussion relative to culvert modeling is provided below in Section V-04.06.

6. End sections shall be used on all culverts.

7. Multiple pipe installations shall have a minimum space of 1.5 feet between the flared end sections. Stationing for culverts needs to be established based upon the largest diameter culvert alternative, and the widest end section that could be used. Corrugated steel pipe culverts will generally be a larger diameter as compared to the smooth-walled alternatives, and the steel end sections are also wider at their outer ends. Therefore, culvert locations most often need to be based upon dimensional requirements of the corrugated steel pipe alternative.

8. Where practicable, when culvert extension is necessary, culverts should be extended so that the open portion of the end section is beyond the clear zone.

9. Where practicable, all culverts shall be sized such that the discharge velocity does not exceed 10 feet per second. Modeling and installation of broken-back culverts in order to reduce outlet velocity is acceptable, and encouraged. Refer to Section V-04.08 for a discussion of broken-back culverts. If sizing and culvert slope adjustments cannot practically limit discharge velocity to 10 feet per second or less, then some form of outlet erosion control should be provided. See Section V-04.07 for a discussion of energy dissipation. Most often, the installation of riprap is the preferred measure. In some areas where very poor soils are prevalent, such as in the badlands, the use of riprap for discharge velocities of 7 feet per second or higher may be warranted. Sizing of riprap aprons is addressed in Section V–04.07.

10. Headwater elevations shall comply with the requirements of Article 89-14 of North Dakota Administrative Code. For new centerline culvert installations, it is preferred that all crossings be sized to adequately convey the 100-year discharge without overtopping

of the roadway. It is recognized that while this practice is desirable, it may not be practical at all locations to achieve such protection from overtopping. An example of such a location may be where pipe crossings are within a floodway, where the road may overtop during extreme events.

11. It is required that 100-year flood data be provided in the hydraulic data in Section 50 of the plans for centerline culvert crossings.

12. Changes to the established drainage patterns, which result in water being discharged from the highway right of way at a different location than where it presently discharges should not be made without the direction of the respective Water Resource District.

13. Care shall be taken to maintain culvert invert elevations for existing centerline and approach culvert crossings, unless minor adjustments are necessary to match a culvert crossing to the upstream and downstream channel due to extension of the culvert length.

V–04.03 Determination of Drainage Areas

The following procedures shall be used in determining the drainage area:

1. Drainage areas shall be outlined on county maps, aerial photographs, U.S. Geological Survey Contour Maps, or specially prepared maps. Typically this task is accomplished using ArcGIS or some similar GIS software.

2. All drainage area boundaries shall be drawn from the highway centerline, surrounding the area being covered, and closing again at the centerline. Note any exceptions to this on the map. These notations shall show location, and if possible, elevation of break-over or diversion to or from the drainage area.

3. It should be shown on the map when two or more culverts operate together to drain an area.

4. Drainage areas for each centerline culvert requiring analysis, and for any approach culvert crossing requiring analysis shall be represented on a contour map. Along with the stationing of each crossing, the longest drainage path, and drainage area in acres, shall be listed. All pertinent data required to calculate the discharge for each culvert shall be summarized, either on the map, or in a separate table.

5. At locations where accurate delineation of the drainage areas from maps is difficult, the map information should be supplemented with a survey, or there should be a field review of the project to verify the drainage area.

V–04.04 Determination of Design Discharge

Peak discharge shall be determined in accordance with Section V-01.04 of the Design Manual. Most culverts are rural installations, so the USGS regression equations will most often be used.

V–04.05 Allowable Headwater

Allowable headwater shall comply with Article 89-14 of North Dakota Administrative Code. The culverts for field drives and private drives shall be sized using a 10-year discharge, the same as is prescribed for township roads.

When sizing the culverts for approach roadways (including township or county roads, and field or private drives), the headwater developed upstream from the approach roadway needs to be compared to the mainline roadway. At some locations, such as where the adjacent land is higher than the mainline roadway, the headwater developed upstream from an approach culvert may result in flooding of the mainline. At these locations, the approach culvert needs to be sized to provide similar protection from flooding of the mainline as would be required of a centerline culvert.

Potential damage to adjacent property or inconvenience to the owners should be of primary concern.

The allowable headwater should be compared to the elevation of the watershed's natural divides. It may be necessary to construct ditch blocks so a culvert may operate efficiently and to prevent flow from one drainage area to another.

V–04.06 Modeling and Selection of Culvert Size

Pipe culvert modeling shall be performed using the FHWA's HY-8 software in order to determine the proper culvert sizes required. Headwater depth, outlet velocity, tailwater depth and Froude number shall be determined using the HY-8 software.

At a minimum, the model for each crossing shall include the 2-year discharge, the design discharge, and the 100-year discharge.

Tailwater conditions, including Manning's n value, slope, channel bottom width, and side slopes of the downstream channel shall be estimated using contour maps, photographs, aerial photographs, and if necessary, site visits. These data shall be incorporated into the modeling of each crossing. Roadway ditches, and most natural and man-made channels are most often appropriately modeled as trapezoidal channels. Where a reservoir, weir, or some other feature controls the tailwater elevation, modeling should take this into account, and the use of either a rating curve, or constant tailwater elevation may be necessary to accurately model the crossing.

Inlet configuration shall be modeled as "Square Edge with Headwall" for all pipe culvert types with either standard end sections or traversable end sections.

Manning's n value for smooth-walled (RCP or spiral rib corrugated) shall be 0.012, and the n value for corrugated steel pipes shall be 0.024.

For reference, Appendix V-04A provides an example of a delineated drainage area, design discharge values, and an example HY-8 Report.

V–04.07 Energy Dissipation

The following is a guide for energy dissipation at the outlet ends of culverts:

1. Riprap shall be used when the discharge velocity of a culvert exceeds 10 feet per second. Generally where the Froude number is less than 2.5, a riprap apron will provide sufficient energy dissipation. Table 10.1 of HEC 14 lists classes of riprap with rock size, apron length, and apron depth. This table shall be used along with the method described in Section 10.2 of HEC 14, except that maximum riprap apron thickness shall be limited to 3 feet. Table 10.1 of HEC 14 specifies riprap classes, from Class 1 to Class 6. The apron length and depth shall be dimensioned in accordance with Table 10.1. In the project plans, NDDOT Grade 1 riprap shall be specified where class 1, 2, 3 or 4 riprap is indicated by the table, NDDOT Grade 2 riprap shall be specified for Class 5 riprap, and NDDOT Grade 3 riprap shall be specified when Table 10.1 indicates Class 6 riprap. NDDOT riprap gradations are provided in Section 256 of the Standard Specifications.

   Individual sizing of riprap aprons for each culvert that has a high discharge velocity (typically exceeding 10 feet per second in most areas) on a project is not always necessary. Riprap apron dimensions shall be sized for each culvert diameter for which riprap is necessary on a project. The worst-case (highest velocity, highest discharge, highest Froude number, or some reasonable combination) culvert of a particular size should be analyzed, and then the riprap apron dimensions which have been determined for that culvert shall be used for all other high-velocity (requiring riprap) culverts of the same diameter on the project. For example, if there are three 30-inch diameter culverts on a project having discharge velocities of 11, 14 and 15 feet per second, and Froude numbers of 1, 1.2 and 1.3 respectively, with discharges of 28, 33, and 40 cfs respectively, the culvert with 15 feet/sec. velocity, Froude number of 1.3, and discharge of 40 cfs would be used for sizing the riprap apron for all three of these culverts. In some cases, where velocity, Froude number and discharge do not increase correspondingly, engineering judgment may be necessary to determine which culvert to use for riprap sizing. When uncertain, size riprap for more than one location, and use the largest apron size in the plans for all similarly-sized culverts with high velocities on a project.

   Articulating concrete block mats can be used where it is necessary to provide energy

dissipation within the clear zone of a roadway. When installed properly, these mats do not present an obstruction to errant vehicles.

2. Where reinforced concrete pipe culverts are used, and discharge velocity cannot be reduced sufficiently by a reasonable culvert size adjustment, or via the use of a broken-back installation, the use of baffle rings may be beneficial in some cases. These rings restrict the normal flow causing a hydraulic jump within the culvert, resulting in a reduced outlet velocity. The design and spacing of the rings are such that the culvert will flow full at design discharge. Baffle rings should only be considered when the discharge Froude Number is greater than 2.5, and where culvert slope is approximately 3% or higher. The viability of baffle ring energy dissipation can be determined using FHWA's HY-8 software. Baffle rings are not available for culvert types other than RCP.

3. Energy dissipators such as blocks, sills, or other roughness elements used to impose exaggerated resistance to flow, may be required when the outlet conditions can't be controlled with the above measures.

V-04.08 Broken-Back Culverts

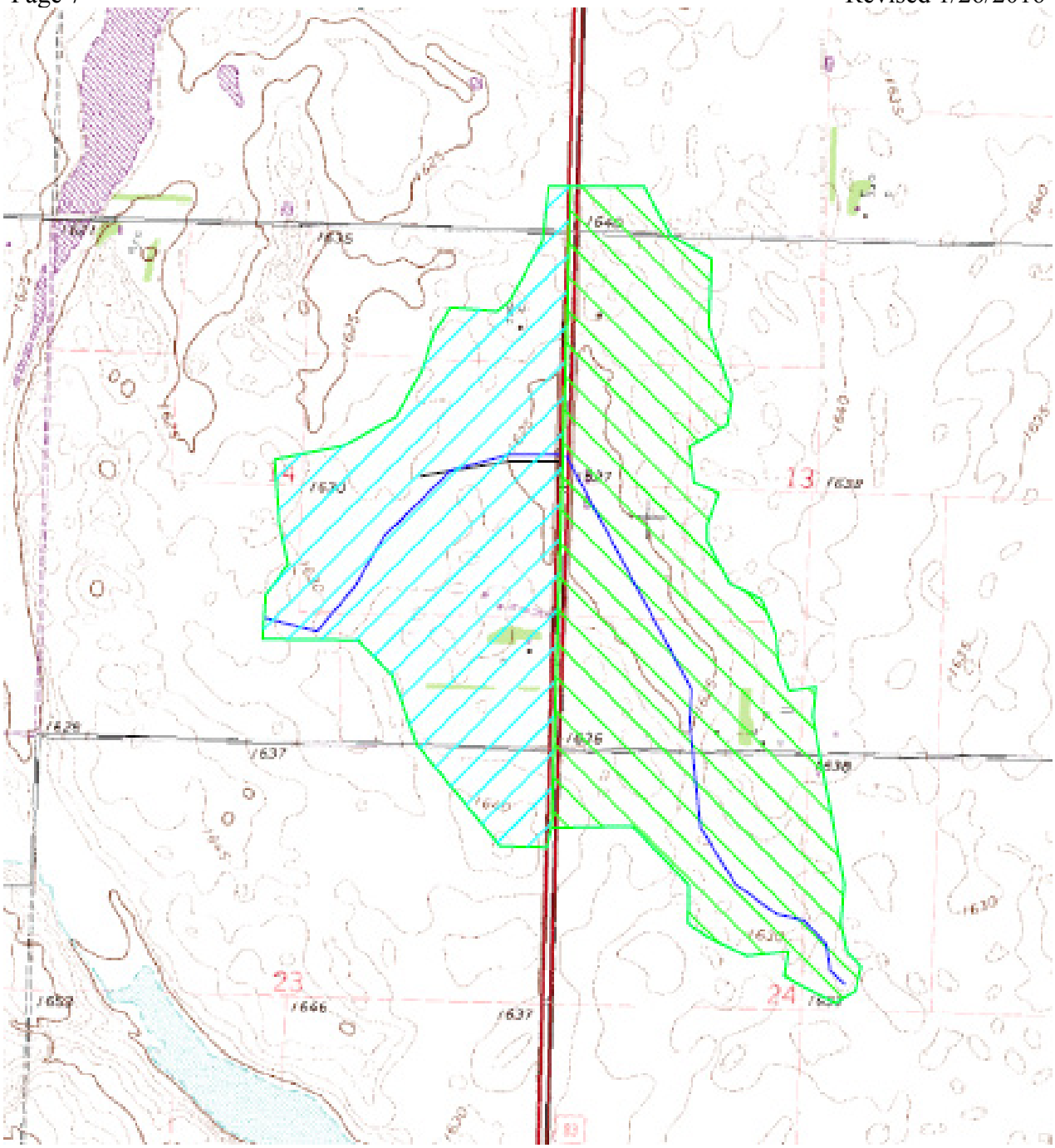
Broken-back culvert installations may be modeled using either FHWA's HY-8 software or Nebraska DOT's BCAP broken-back culvert program.

For all sizes of RCP culverts, deflection angles shall be achieved by distributing the total required deflection angle between multiple culvert sections, using a maximum of 1 degree of deflection per joint. The plans shall specify how many joints are deflected, and the deflection angle for each joint. Mortar and filter fabric shall be installed on all open joints, and this also shall be specified in the plans.

For culvert types other than RCP, prefabricated bend sections will need to be furnished to accomplish the required deflection. The plans need to specify the bend angle required.

V-04.09 Sizing of Equalizer Culverts

The method provided in the example below in this section, which takes into consideration the drainage area and flows from each side of the highway, shall be used for sizing equalizer culverts. The size of the culvert is determined by distributing the total discharge proportionately to the storage areas on each side of the road. It is generally assumed with this method, that storage volume is proportional to storage area. As a brief example of this method, consider the closed basin depicted on the following page.



USGS Regression Equation Calculations are performed to determine the contributing peak flow from each of the two sub-basins. Hydrologic Data for each of the sub-basins for this example are provided below.

Drainage Area = 258.6517 acres
Drainage Path = 3847'
Drainage Path 10% = 384.7' - Elev = 1624'
Drainage Path 85% = 3270' - Elev = 1630'
Basin Slope = (1630' - 1624') / (3270' - 384.7')
= .002 ft/ft

USGS REGRESSION RESULTS

Contributing Drainage Area	Channel Slope	Hydrologic Region
259 Acres	.002 Ft/Ft	Region C

RESULTS

Recurrence Interval (years)	Peak Flow Q
2	5 CFS
10	23 CFS
15	30 CFS
25	39 CFS
50	53 CFS
100	69 CFS
500	111 CFS

Location
West Side of Basin

Drainage Area = 334.7083 acres
Drainage Path = 6477'
Drainage Path 10% = 648' - Elev = 1621.5'
Drainage Path 85% = 5506' - Elev = 1630'
Basin Slope = (1630' - 1621.5') / (5506' - 648')
= .0017 ft/ft

USGS REGRESSION RESULTS

Contributing Drainage Area	Channel Slope	Hydrologic Region
334.71 Acres	.0017 Ft/Ft	Region C

RESULTS

Recurrence Interval (years)	Peak Flow Q
2	6 CFS
10	26 CFS
15	34 CFS
25	44 CFS
50	61 CFS
100	79 CFS
500	128 CFS

Location
East Side of Basin

Using the 25-year peak discharges, the total peak flow to the basin is summed as: 39 CFS (on the west side of the highway) + 44 CFS (contributed from the east side of the highway) = 83 CFS.

The storage area, determined from a contour map using Arcmap software, is determined, and then divided at the highway. For this example, the total storage area was found to be 63.27 acres, with the storage on the west side of the highway determined to be 11.57 acres, and the east storage area was determined to be 51.7 acres. With less storage on the west side of the highway, and nearly equivalent discharges on each side, it is apparent that equalization flow will be from west to east.

The flow is distributed proportionately to the two storage areas as follows:

Q_W = 83 CFS * (11.57 Ac/63.27 Ac) = 15.18 CFS

And,

Q_E = 83 CFS * (51.7 Ac/63.27 Ac) = 67.82 CFS

Since 67.82 CFS of the total flow is distributed to the east storage area, resultant flow, as was previously assumed, is from west to east to equalize the slough. The resultant equalization flow is then determined by subtracting the discharge distributed to the west storage area above from the discharge originating from the west sub-basin, as follows:

Q_{25} = 39 CFS – 15.18 CFS = 23.82 CFS

The crossing is then modeled in HY-8, generally using a fixed tail water elevation to determine culvert size.

At locations where flows may become more ‘directional’ due to the overflow of a closed basin, it may be necessary to increase the size of equalizer culverts to accommodate the unidirectional flow. In these cases, the culvert is essentially acting as a typical stream crossing, and typical culvert sizing methods shall be used.

V–04.10 Grade Raise Analyses for Closed Basins

Grade raises through closed basins are generally constructed for roadways with imminent risk of inundation, or roadways that are currently inundated by the adjacent water body or basin.

Typically, 3 build alternates are proposed for a given grade raise project:

1. Grade Raise above the natural outlet elevation
2. Grade Raise above the 3-year forecast water surface elevation
3. 5’ Grade Raise above the existing water surface elevation

The natural outlet elevation for the basin shall be determined by survey. The grade raise analysis shall include an estimate of the 3-year forecast water surface elevation, and should estimate the time forecast when the storage of the basin will reach the natural outlet and/or exceed the 5' Grade Raise elevation. Riprap shall typically be placed 2' above the 3-year forecast water surface elevation. In some cases, where higher waves are anticipated, such as locations with long fetches, riprap may be necessary to a higher elevation.

The NDDOT monitors closed basins which may threaten adjacent state or interstate highways by obtaining water surface elevations via ground survey at approximately one-year intervals. The 3-year forecast water surface elevation shall be determined as follows:

1. Based upon two (past and present) elevations, the basin storage volume which has been occupied by the rising water during a known time will be determined using contours or other geographical data.
2. Assuming that present meteorological/hydrologic conditions will prevail for 3 years into the future, the storage volume which will be occupied by future precipitation will be estimated by extrapolation/interpolation to arrive at a 3-year forecast storage volume.
3. The 3-year forecast rise in water surface elevation shall be determined using the 3-year forecast storage volume and contours or other geographic data.

V–04.11 Hydrologic and Hydraulic Data to be Submitted with Deliverables

For consultant-prepared plans, the following hydrologic and hydraulic data for the Milestone Activity "Roadway Hydraulics" (RDHYD) shall be retained and submitted electronically concurrently with the PS&E plans for a project:

1. Drainage area maps with contours showing each centerline and approach culvert. At a minimum, longest drainage path, drainage area, and stationing for each culvert shall be shown on the map. See Appendix V-04A for an example showing a single culvert crossing. Multiple crossings may be shown on each map, provided that information is clear and legible. Separate sets of maps may be appropriate to show centerline and approach culverts.

2. A summary of the hydrologic data for each drainage area, including, at a minimum, USGS region, slope of the upstream channel, 2-year, design discharge, and 100-year discharge values. In the example in Appendix V-04A, this data is shown on the drainage area map. This data is often tabulated by various engineers in spreadsheets, and the output from the spreadsheet or other software will be sufficient. Provision of this data on the drainage map is not necessary.

3. An HY-8 Culvert Analysis Report for each crossing. Appendix V-04A provides an example HY-8 report for reference. A report for each crossing shall be prepared for each alternative culvert type and size. The report for each crossing shall include the following information:

A. Summary of Culvert Flows
B. Culvert Summary Table
C. Water Surface Profile
D. Downstream Channel Rating Curve Data
E. Tailwater Channel Data
F. Roadway Data

4. ArcGIS or other GIS computer files, HY-8 computer files, and any other spreadsheet or computer files used to calculate peak discharge, riprap sizing, or any other hydrologic or hydraulic-related computer files shall be submitted. HY-8 files shall include the analysis of each crossing for both the existing and proposed conditions. The report generated by HY-8 (as discussed in item 3 above) only needs to include the information for the proposed culvert.

V–04.12 Standard Drawings Pertaining to Highway Culverts

Standard	Description
D–714–1	Reinforced Concrete Pipe Culverts and End Sections.
D–714–2	Reinforced Concrete Pipe Arch Culverts and End Sections
D–714–4	Corrugated Steel Pipe Culverts and End Sections
D–714–5	Corrugated Steel Pipe Arch Culverts and End Sections
D-714–11	Traversable End Sections for Corrugated Steel Pipe Culverts
D-714–13	Reinforced Concrete Pipe Baffle Rings
D–714–16	Jacked and Bored Pipe