Objectives and Purpose . . . . Page 1
Open Bottom Arch - Flow Model . . . . Page 1
The Pros and Cons of Metal Arch Culverts . . . . Page 2
Positive Features of Arch Culverts. . . . . Page 2
Negative features of Arch Culverts . . . . Page 2
Design of Open Bottom Arch Culverts . . . . Page 3
Design of Footings for Open Bottom Arch Culverts . . . . Page 4
Arch Footings . . . . Page 4
Bearing Capacity of Foundation . . . . Page 5
The Selection of Footing Dimensions and Details . . . . Page 6
Rise/ Span ratio . . . . Page 7
B1= Width of a Rectangular Concrete Footing under arch . . . . Page 8
B2 = Width of Stem wall . . . . Page 8
BE =Offset of Center of bearing from Stream Face of Footing . . . . Page 9
H1,H2,H3, and H6= Height of the Footing . . . . Page 9
Riprap Embedment Depth between footings a commentary . . . . Page 10
Forces on Arch Footing . . . . Page 10
W2 and W3- Soil Loading -Dead Loads: . . . . Page 12
P1 and P2- Soil Pressure on Backfill . . . . Page 12
Design Method- Service Load or Allowable Stress . . . . Page 12
Service Load Method Values for . . . . Page 12
Typical Dimensions of Footing with stem walls . . . . Page 13
Open bottom Arch with Concrete Footings- PHOTOS . . . . Page 14
Open Bottom Arch Culverts with Metal Footing Pads . . . . Page 15
Applicability of arches with metal footing pads . . . . Page 15
Selection of metal footing pads . . . . Page 15
Open Bottom Arch with Metal Footing Pads- PHOTOS . . . . Page 16
Design of footings for arch culvert with metal pad footings . . . . Page 18

Chapter 6: OPEN BOTTOM STRUCTURES

Objectives and Purpose

This chapter discusses the features of open bottom arches and provides design recommendations for thier use. stream simulation. Open bottom structures discussed in this chapter include

1. Pipe arches with concrete footings
2. Pipe arches with metal footings

Open Bottom Arch - Flow Model

The hydrology and sizing of open bottom arches is similar to those for designing pipe arches and culverts. Charts solutions are available in most design manuals. Design programs such as" FishXing" and "Culvert Master" are recommended.

Fish passage through the structures assumes stream simulation. Fish will move between the rocks which provide protection and points of low velocity. An arch culvert may constitute a partial barrier to fish passage if the arch constricts the stream or spans a bedrock chute.

An outlet control boulder weir is recommended for arches. The control weir creates a energy dissipation pool to prevent down cutting at the culvert outlet, and a backwater into the culvert. The rock control weir should be designed to backwater to the top of the embedment riprap or design substrate grade at the outlet of the culvert.

Stream simulation can be improved in open bottom structures such as arch culverts by placing boulder clusters in and below the culvert to capture substrate and provide low velocity areas.

Foundation or footings must be erosion resistant. This author's preference is to always embed the arch with rock that is scour resistance. Geotextile is optional but not recommended.

The Pros and Cons of Metal Arch Culverts

Positive Features of Arch Culverts.

1. Provides a rock or gravel substrate for stream simulation.
2. When width = bank full or larger, an arch can provide passage for wildlife in addition to fish.
3. An arch allows the use of large rock for substrate and scour protection. Accordingly an arch can provide stream simulation for grades greater than 7%.
4. Footing heights on arches can be adjusted. Using tall footings an arch will allows for fluctuations of gravel bars at the confluence of smaller streams with larger streams.
5. An arch culvert footing is preferred on rock foundations eliminating the need for rock excavation and blasting when the base rock is not ripable.

Negative features of Arch Culverts

3. A metal arch is less cost effective than pipe arch culverts for spans less than 13 feet.
4. Concrete arch structures are often preferred to metal arch structure for the following reasons. They resemble bridges in their construction and have higher clearance for debris flow than arches of the same width. They can with stand the forces and impact of a debris flow and are preferred at sites with overtopping risks. Concrete arches can be designed as bridges with no cover requirements.ootings for arch culverts take longer to install than alternatives without footings. Construction requires additional time. Delays affect seasonal restrictions, weather, and traffic and total costs of the project.
5. An arch culvert like other culvert options may be a barrier to movement of large woody debris.
6. Metal arches have limitation on minimum cover. Maximum cover is normally not an issue.
7. Arch culverts should not be placed in areas where foundations are questionable.
8. Footings must be protected from scour and subsurface flows. An arch should never be constructed on an existing fill.
9. Metal arches can **fail dramatically** if flows overtop road and fill is washed out or if footings are scoured and undermined.

Design of Open Bottom Arch Culverts

I. Select an arch size that will pass the desired design flow with a minimum size equal to the active channel or bankfull width of the existing stream.

A. Size for peak flow using manual methods per FHWA handbooks or proprietary programs such as "Culvert Master" or" FishXing" .

B. Adjust size for stream simulation . Use a minimum span width equal to the active or bank full width as defined in chapter three.

II. Select a structure with adequate freeboard height to past debris during peak events. Bridge structures often have 4 foot of freeboard to allow floating debris to pass under the superstructures. Major arches should have at least 2 to 3 feet of freeboard. Provide sufficient head for movement of debris through the structure.

III. Protect the footings and foundation from scour and erosion. Use method that considers both velocity and Depth during peak flow events. Mitigate peak flow effects by

1. Adding roughness and scour protection with riprap embedment for the full width and length of the culvert.
2. Reducing the gradient of flow through the culvert
3. Widening the span which will lower the velocity and depth..
4. On steep gradient structures the width of the arch may be controlled by the riprap size. As the gradient increases the riprap must be sized larger to prevent scour. Widening the channel will reduce the depth and velocity of flow within the culvert.

IV. Compare the outlet velocity at peak flows events against the velocity of the natural channel. If the difference between those velocities are excessive add an outlet dissipation basin or widen the culvert.

V. Check the backwater height during peak flows events. Verify that the backwater will not extend beyond road right of way limits or damage property. Consider widening culvert to lower backwater. See discussion on the affect of back watering at the confluence of two streams in chapter two.

VI. A special case exists when open bottom structures outlet into a main channel. The footings on these structures often need to be taller at the outlet. Gravel deposition will raise to the level of the main stems bank full elevation during high annual flows. Adding extra height to the footing will prevent the outlet from becoming restricted or blocked.

VII. Design the outlet for two flow conditions. The first condition is when gravels degrade to the level of the low flow elevation of the main channel The second condition is when the gravels aggrade to the level of the bank full elevation of the main channel. The riprap level, or top of the rock in the structure should be designed for back-watering from the lowest possible level. Taper the footing for these contingencies.

VIII. Select an arch shape. The following calculations are required by AASHTO and should be completed and kept with the culvert files. The pipe manufacturer's will often provide these calculations..

1. (1) Wall Area of pipe
2. (2) Buckling strength

3. (3) Seam resistance for structures with longitudinal seams

IX. Check design for Flexibility, minimum cover and maximum cover in accordance with the appropriate AASHTO specifications.
X. Select materials and gage : Aluminum, Aluminized Steel, Galvanized Steel. Add extra thickness if corrosion is a concern.
XI. Design Footings for Arch.

Design of Footings for Open Bottom Arch Culverts

Open bottom structures should be placed on foundations that have high bearing capacity and low potential for settlement such as a gravel or rock foundations. Do not install open bottom structures on soft or erodible soils. Footing design shall comply with the AASHTO Design Bridge Design Specifications.[1]

The design of footings is normally an engineering responsibility with guidance from codes and standard practice.

Arch Footings

I. Avoid designs that prevent settlement. An arch is a flexible structure designed to yield with the adjacent side fills. There should be uniform longitudinal settlement in the footings to avoid drag down forces from the adjacent side fill
II. Remove poor material and replace with acceptable material around footings
III. " Footing reactions for the metal arch are considered to act tangentially to the metal plate at the point of connection to the footing. The value of the reaction is the thrust in the metal arch plate at the footing.
IV. "Footings supported on soil or degradable rock strata shall be embedded below the maximum computed scour depth or protected with rock or a concrete floor a scour countermeasure. Footings supported on massive, competent rock formations which are highly resistant to scour shall be placed directly on the cleaned rock surface. Where required, additional lateral resistance should be provided by drilling and grouting steel dowels into the rock surface rather than blasting to embed the footing below the rock surface."[2]

[1] AASHTO LRFD Bridge Design Specifications, 1994 edition.12.6.2.2.4

[2] AASHTO, Standard Specifications for Highway Bridges, 16^{th} edition, 4.4.5.2.

Bearing Capacity of Foundation

The bearing capacity of the footings is calculated from the formulas for general shear failure. See Chapter two. The following relationship is used for continuous footings where L> 5B

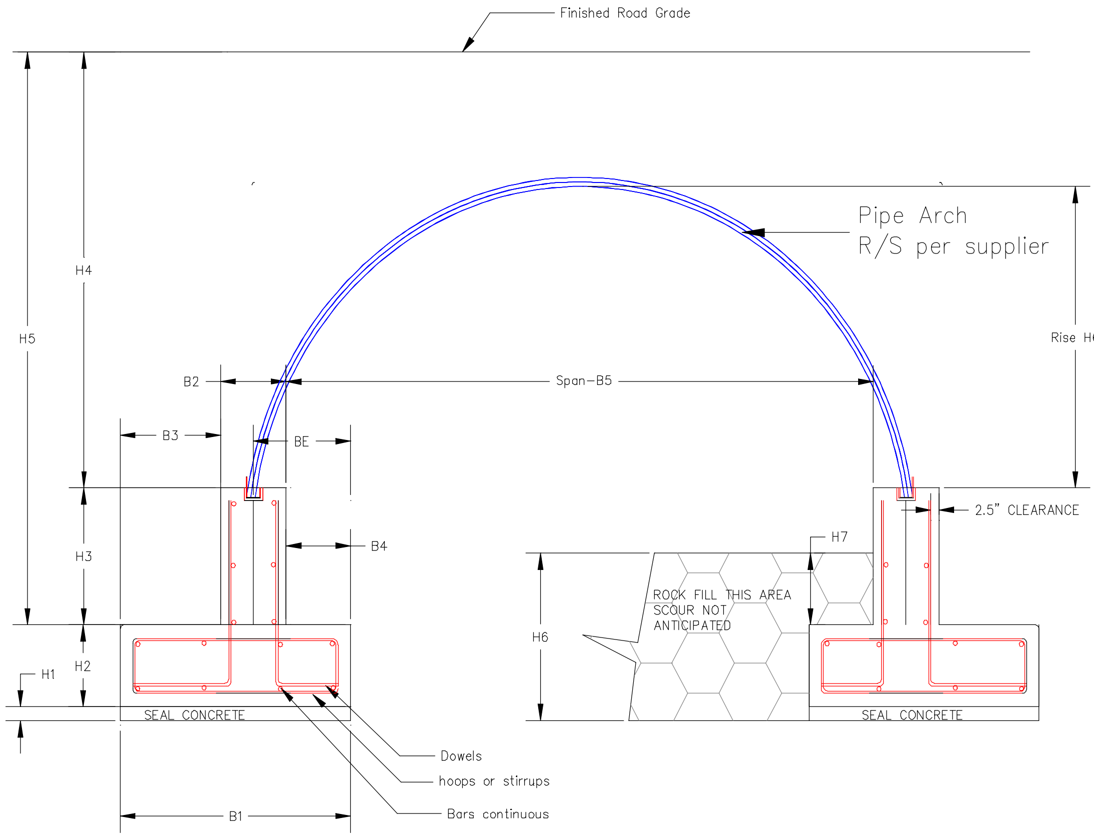
Qult= Cnc +0.5 YBNy + qNq

Qult using the equation above is affected by

- Depth of groundwater below foundation which is zero for an arch in a stream.
- Depth of surcharge adjacent to the foundation on the stream side of the footing
- The width of the footing B
- The friction angle "phi" of the foundation material. Use undrained strengths in areas of high ground water.

The Selection of Footing Dimensions and Details

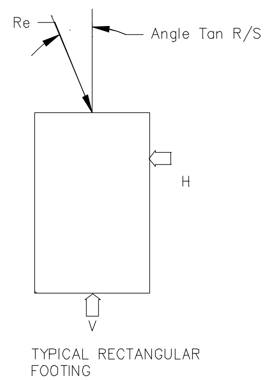
The most common footings are rectangular footings or rectangular footings with stem wall. A drawing of a typical footing is detailed below.



Footing Dimension Variables

Rise/ Span ratio

The forces applied to a rigid concrete footing by an arch structure are diagramed below.



RE= Reaction Load from Liveload, fill and dead load of culvert and Foundation
V= Footing Vertical Load uniformly distributed not to exceed bearing capacity of soil.
R/S = Ratio of Rise of arch to span of arch
H= Footing Horizontal Trust

The top of the footing slope may be tapered to match the angle of contact of the forces from the culvert to the top of the footing. That angle is a function of the Rise to Span of the culvert. A table was developed below which gives values of the angle and the slope of the footing required to match the various R/S ratios.

When the R/S is other then 0.50 there is a horizontal as well as a vertical component of loads transferred to the footings.

The following table gives the relationship between the Rise and Span and the angle of contact of the forces with the top of the footing.

Table 9.1 Footing slopes to match R/S

R/S	degree	X= inches in foot of Footing
.5	0	0
.48	2	1/4
.46	4.4	1
.44	7.0	1-1/2
.42	9.5	2-1/8
.40	12.0	2-11/16
.38	15	3-5/16
.36	18.2	3-7/8
.34	21.5	4-5/8
.32	25.0	5-1/2
.30	28.2	6-3/8

Using the table above we can calculate the Horizontal and Vertical loads on the footings for the various R/S ratios

V= Vertical load= Re x Cosine (phi) + Footing Deadload
H= Horizontal load= Re x Sin(phi)

B1= Width of a Rectangular Concrete Footing under arch

The footing width is sized to provide adequate bearing for the structure without exceeding the bearing capacity of the soil below.

B2 = Width of Stem wall

The minimum Stem wall width should include at least 6 inches of shear concrete between the edge of the channel or slot and the face of the stem wall. A steel channel is often selected to secure the arch to the footing. A typical channel is 3 inches wide. Accordingly the minimum width of the stem wall should be 15 inches.
An alternate design for arches with spans less than 15 feet is to use an 8 inch x 4 inch slot in the footing without a channel. The slot is filled with non shrink grout after the arch is installed. Anchor bolts are not required. The minimum width of the footing for this design is (6" + 8" +6") 20" inches. Care must be

taken to set longitudinal reinforcement 2" below the top of the footing for shear loads during construction. Use this design when R/S is approximately 0.50.

BE = Offset of Center of bearing from Stream Face of Footing

The distance BE is calculated for each design. The objective is to set the center of bearing of all the forces on the footing within the middle 1/3 of the footing Base. The location of BE will determine lengths B3 and B4.

H1,H2,H3, and H6 = Height of the Footing

I. The height of the footing is established from the following criterion.

II. The height must have a minimum thickness to satisfy structural Requirements for shear, moment, and deflection. The footing is a considered a grade beam with a uniform load on a flexible foundation.

III. The footing height must be equal to or greater than the depth of the embedment H6.

IV. Freeboard is left from the top of the embedment rock to the top of the footing to account for pools and stream variations within the channel.

   A. "Footings not otherwise founded on sound non-degrade able rock surfaces shall be embedded a sufficient depth to provide adequate bearing, scour and frost heave protection or 2 feet to the bottom of the footing whichever is greater."[3]

   B. "Footings for culvert shall be carried to an elevation sufficient to secure a firm foundation, or a heavy reinforced floor shall be used to distribute the pressure over the entire horizontal area of the structure. In any location subject to erosion, aprons or cutoff walls shall be used at both ends of the culvert, and where necessary the entire floor area between the wing walls shall be paved. Baffle walls or struts across the unpaved bottom of a culvert shall not be used where the stream bed is subject to erosion. When conditions require, culvert footings shall be reinforced longitudinally."[4]

V. H2= Height of Footing: This author recommends a minimum thickness of 18 inches. Increase this depth as required for structural calculations.

VI. H3 = Height of Stem wall: Designer has option to have a rectangular footing with or without a stem wall. On narrow footings when B1, the width of the footing is less than 3 feet a Stem wall is not considered economical and should be avoided. The ease of construction of a rectangular footing without a stem wall is compared to the cost savings in concrete with the Stem wall.

VII. H1= Seal Concrete. Seal concrete is an option to level a foundation, reduce the reinforced height of a footing or to make field adjustments for material variations.

VIII. H6 = Embedment Depth of Riprap or Substrate.

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[3]AASHTO Standard Specifications for Highway Bridges, 16^{th} edition, 1996, 4.4.5.1

[4]AASHTO, Standard Specifications for Highway Bridges,16th edition, 1996, 6.3,footings

Riprap Embedment Depth between footings a commentary

Riprap is often embedded between the footings to collect substrates and to prevent scouring of the foundation. Riprap for this purpose is sized to retain a stable channel during periods of peak flow. See example calculations in chapter two. The depth of riprap (H^) establishes the required depth of the concrete footings . The riprap is set between the footings and designed not to extend above the footing except for occasional " velocity shadow" rocks.

If the foundation of the arch is on non-erodible rock, riprap is not needed for riprap scour protection.

"Fabric is placed under the embedded riprap to prevent fines from piping and washing out below the foundation rock".[5].

The rock should be angular and interlocked to prevent movement during high flows. Use formulas for sizing riprap discussed in chapter two.

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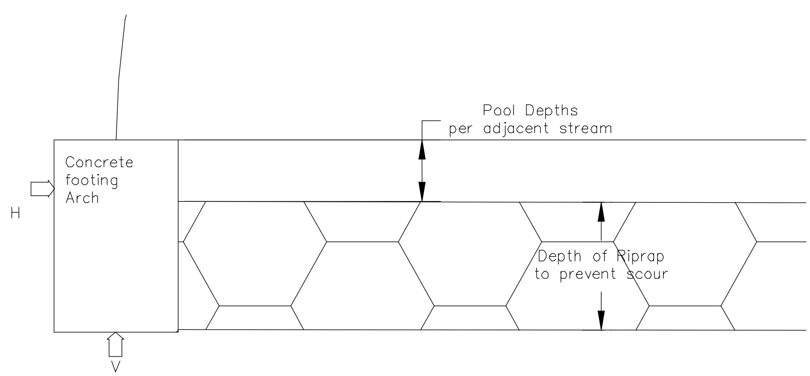
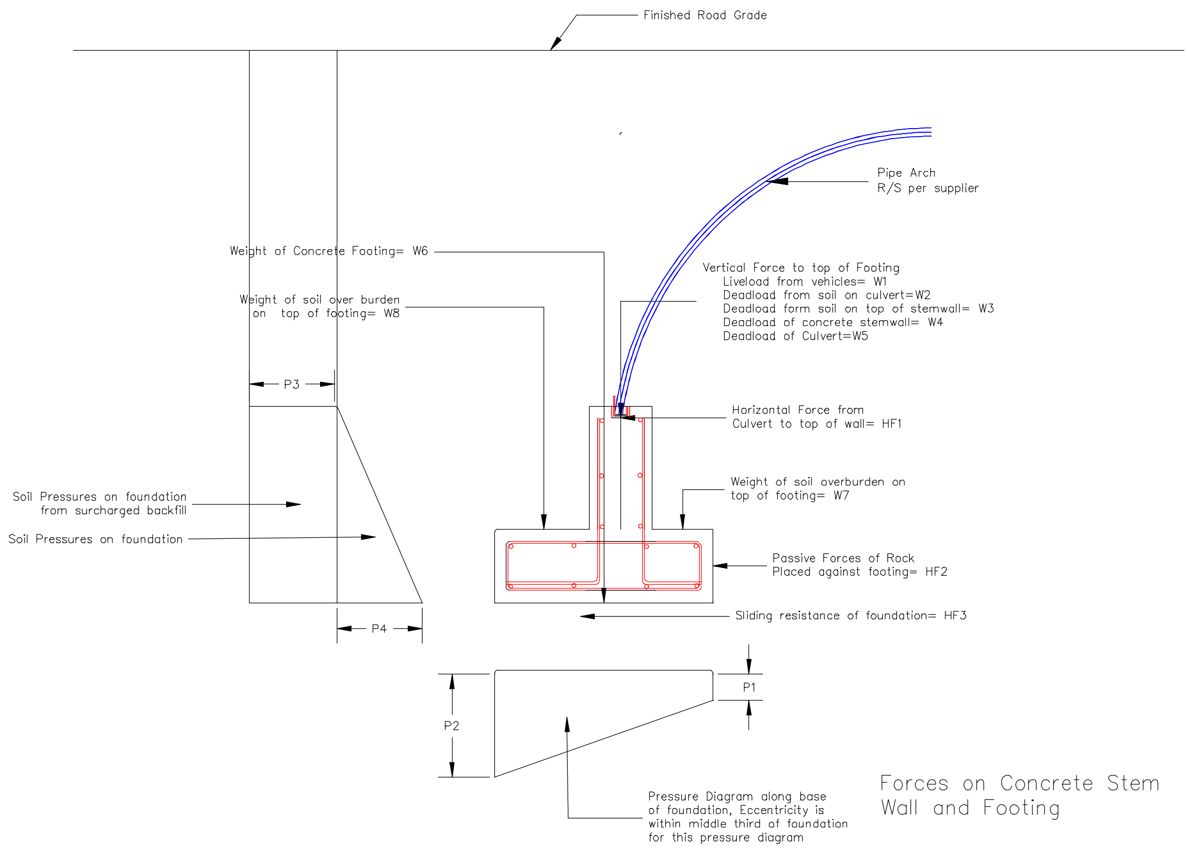


Fo rces on Arch Footing

[5] Standard Specifications for Highway Bridges, 16the edition, 4.4.5.4 piping

W1 Live or Wheel loads:



I. “When the depth of fill is 2 feet or more, concentrated loads shall be considered uniformly distributed over a square with sides equal to 1-3/4 x depth of fill.”[6]

II. “For standard installations, the live load on the pipe shall be assume to have a uniform vertical distribution across the top of the pipe and the same distribution across the bottom of the pipe as given in figure 17.4A for earth loads”[7]

III. “For simple spans the effect of live load may neglected when the depth of fill is more then 8 feet and exceeds the span length;....When the depth of fill is less than 2 feet the wheel load shall be distributed as in slabs with concentrated loads.”

8

[6]AASHTO, 6.4.1 Distribution of wheel loads through earth fills

[7]AASHTO, 17.4.4.2.3 Live Loads

[8]AASHTO, 6.4.2

W2 and W3- Soil Loading -Dead Loads:

"Minimum soil loads are 120 pcf for vertical earth pressure"[9].

P1 and P2- Soil Pressure on Backfill

AASHTO provides two options either the use of approved soil engineering methods or an equivalent fluid weight of 30 psf for lateral forces. This authors preferences is to select the soil type from the design materials specified than to calculate the equivalent fluid weight based on "at rest " conditions.

Design Method- Service Load or Allowable Stress

AASHTO references footing design to the following codes. All are under the SERVICE LOAD method of design or allowable stress method

- Shear-critical section 8.15.5.6
- Development length- 8.24- 8.32
- Dowel size- 4.4.11.5.5
- Earth pressure factor- applied to retained soil is 1.5 for flexible culverts[10]
- Shrinkage and temperature reinforcement- AASHTO 8.20
- Protection against corrosion- minimum cover- AASHTO 8.22.1

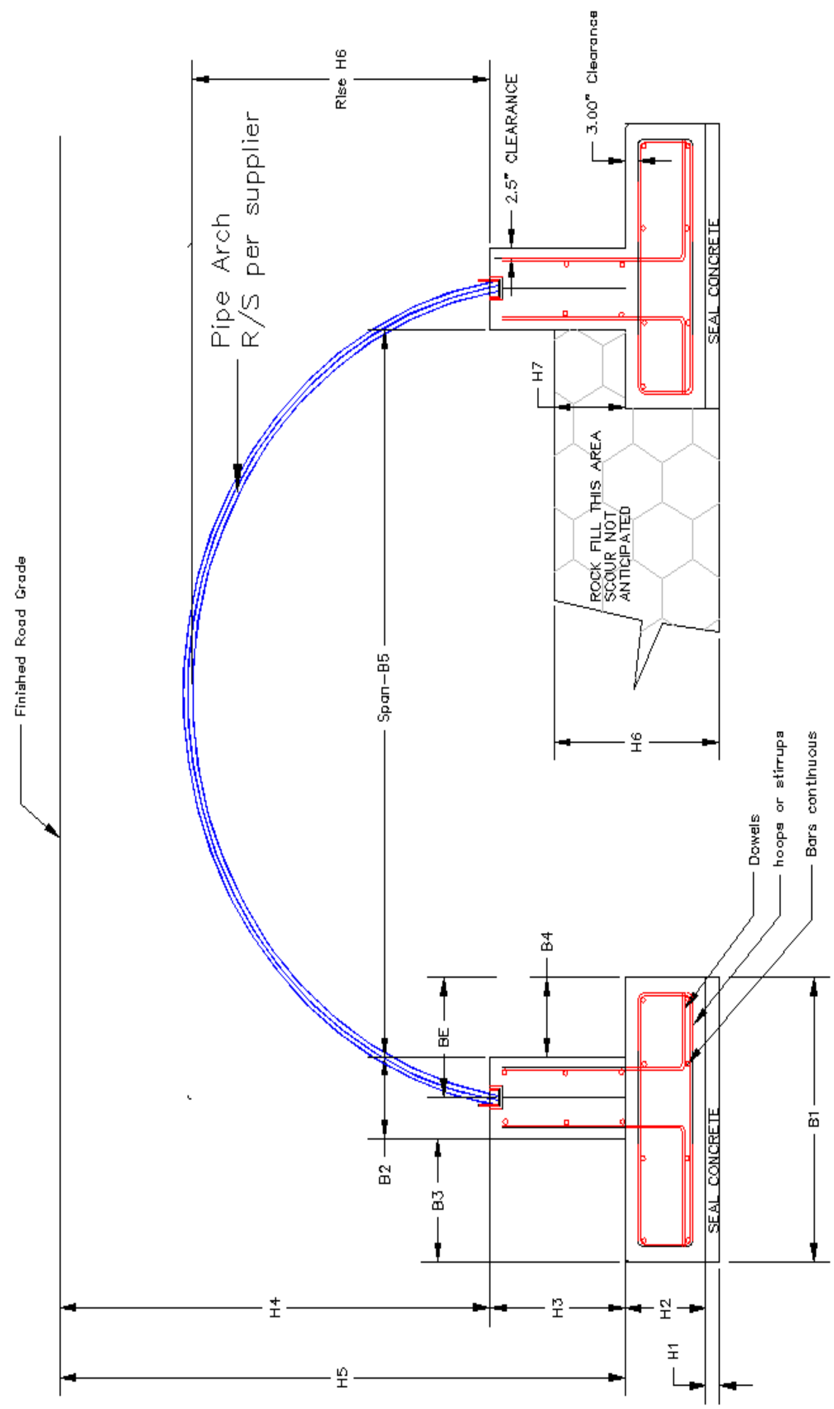
Service Load Method Values for

- fc= fiber stress for flexure design of concrete is 0.40f'c
- ft for grade 60 Reinforcement= 24,000 lbs
- Allowable Shear Stress =0.95 x (fc')^0.5

[9] AASHTO 6.2.1

[10] AASHTO,3.20 and table 3.22.1A

Typical   Dimensions of Footing with stem walls



Open bottom Arch with Concrete Footings- PHOTOS

Photos of a typical installation are shown below.

Photo of a multi plate arch culvert being fabricated on concrete footings

The riprap inside is a critical design element and requires special inspection.

Open Bottom Arch Culverts with Metal Footing Pads

A footing option for arch culverts is metal footing pads. The pads are designed to distribute the vertical or bearing loads from the culvert. Scour is a concern with this option. The pads must set on rock or be placed on a riprap foundation. Its use has been used locally in the Coos Bay Area on a site with an 8 foot width. Contech and Big R both have used this design on sites with spans ranging from 7 to 15 foot. Arch Culverts for this option can be constructed by slicing an 8 foot diameter culvert lengthwise.

Applicability of arches with metal footing pads

1 On streams with non erosive foundations or small flows.
2. As a ditch relief alternative where embedment is desired but head space is limited.
3. On steeper gradient small pipes where large embedment is required that cannot be installed in a circular pipe or pipe arch. Do not install in previous constructed fills.

Selection of metal footing pads

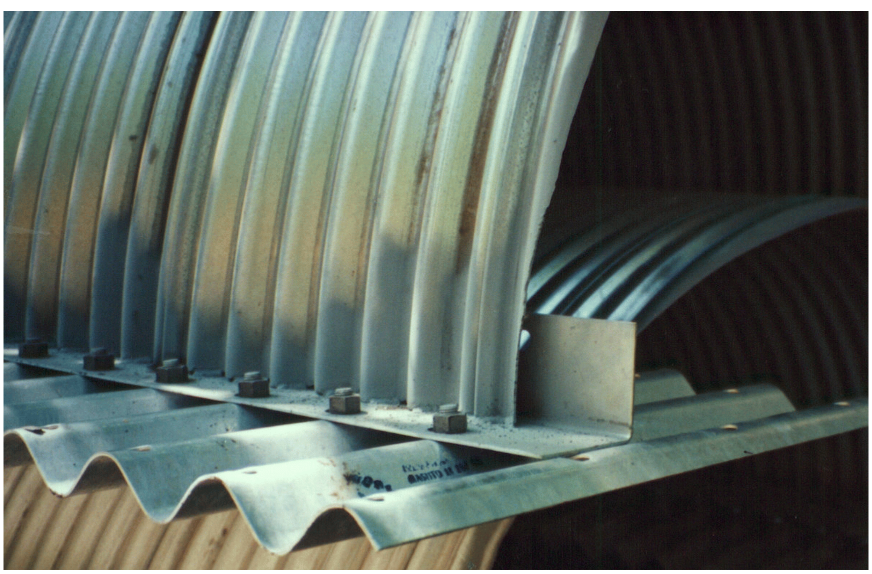
- Footing pads are constructed from existing plates sizes and thicknesses. Select widths that match those sizes.

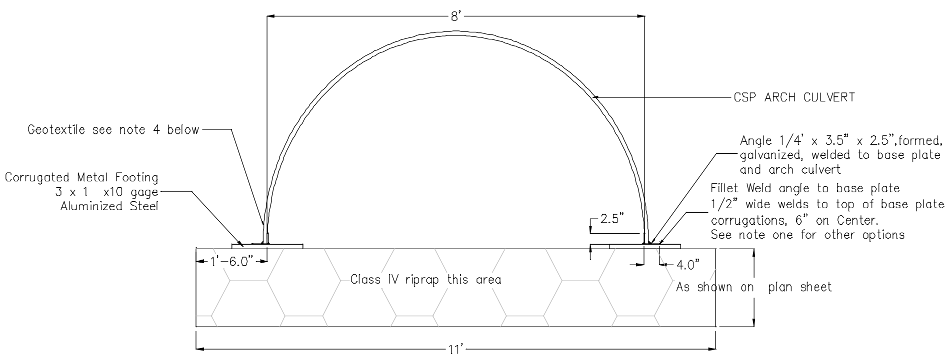
Plate type	Width
9 pi	28 inches
15pi	47 inches
18pi	56 inches
21pi	66 inches

- Horizontal support is not typically required for loads but should be provided during the construction process. Recommend placing wood struts at 15 foot on center between the pads during construction then removing them after. Check horizontal loading on structure for records. Typically the friction between the footings and metal will more then provide sufficient strength.
- This design is only used when the R/S ratio is approximately 0.50.
- If possible after the arch is installed place additional embedment rock within arch for erosion protection and increased horizontal support..
- When setting footings on a rock pad place a leveling pad of 3 inch minus rock under pads. This pad can be enhanced with grout to make a smoother bed for the footing and protect pad from scour.

Open Bottom Arch with Metal Footing Pads- PHOTOS

Photo below was taken inside an open bottom arch with footing pads. The riprap was placed full length on a geotextile to prevent scouring of the foundation. See Base plate detail below.





Elevation View of Arch with Footing Shoes on Riprap

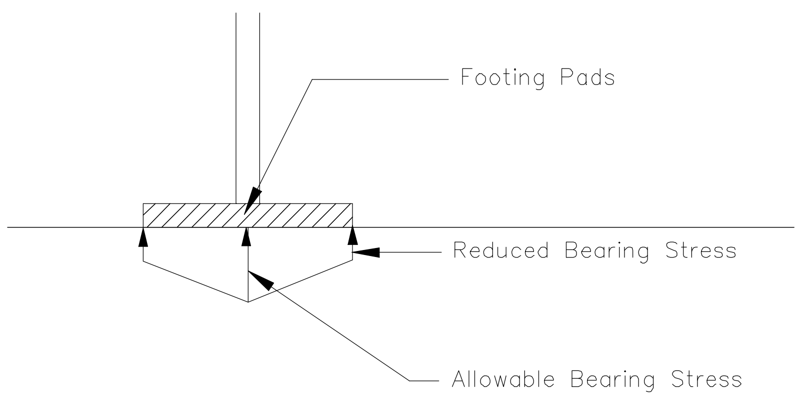
Design of footings for arch culvert with metal pad footings

The following design commentaries were provided by Contech Construction Products.

- ♦ Flexible footing pads are only used with structures that have either no or an insignificant small horizontal footing reaction such as half circle arches and metal box culverts. Thus if the footings were rigid, its width would be:

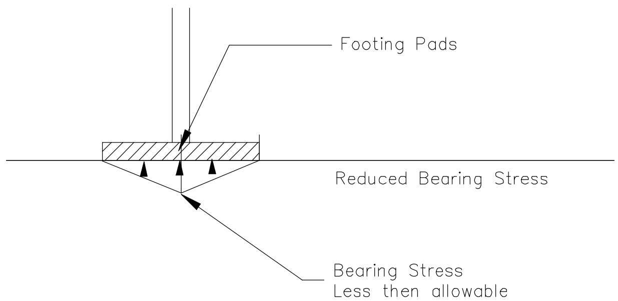
$$W = \frac{\text{Vertical footing Reaction}}{\text{Bearing strength of foundation}}$$

- ♦ However, metal footing pads are not rigid and they deflect somewhat perpendicular to the axis of the structure, thus they typically bear against the foundation soil as shown below.



- ♦ The footing pad itself must be checked for both strength and deflection:
  - ♦ Strength calculations assume one half of the footing pads acts as a cantilever that is fixed at

the structures footing reaction point. Allowable bending is limited to 0.6Fy The foundation bearing pressure acting on the footing pad is as shown.



- ♦ the bearing stress at the outer edge of the footing is calculated so the footing pad develops its full allowable bending strength.
  - ♦ From this pressure distribution, the maximum footing reaction is calculated.
  - ♦ For deflections the footing pad is assumed to bear on 12 inches of soil with a modulus of 1000 psi. This relatively resilient bedding compounds deflections by allowing the center of the footing to settle more than its edges which experience lower bending pressures. As in the strength calculations.
    - ♦ Bearing pressures in the above distribution are calculated so that the settlement into the bedding layer and the deflections of the footing pad match..
    - ♦ From this pressure distribution the maximum footing reaction is calculated.
  - ♦ One condition - that of a very weak footing pad on a very strong foundation- results in a triangular pressure distribution (shown below) with a maximum bearing pressure that is less then the allowable. Thus a weak footing pad may not be able to take full advantage of a very good foundation.