# Design Report

## NRCS – Natural Resources Conservation Service

## Headwall Standard Design

December 2006

PSC Project # 01292604

**Certification: All components comply with the design requirements set forth in the Statement of Work, Texas NRCS Conservation Practice Standard 578, Headwalls and other referenced codes.**

PSC **Parkhill, Smith & Cooper, Inc.**
Engineers ▪ Architects ▪ Planners

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STATE OF TEXAS
JOSEPH R. RAPIER
61147
LICENSED
PROFESSIONAL ENGINEER
12.21.06

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I certify to the best of my knowledge that Texas Standard drawings:

| | |
|---|---|
| **TX-EN-0500** | **Headwalls with Timbers and Steel Pipe Piles**<br>**6 foot maximum height**<br>**Sheets 1 of 5, 2 of 5 and 3 of 5** |
| **TX-EN-0501** | **Headwalls with Timbers and Steel Pipe Piles**<br>**11 foot maximum height**<br>**Sheets 1 of 5, 2 of 5 and 3 of 5** |
| **TX-EN-0502** | **Headwalls with Timbers and Steel Pipe Piles**<br>**16 foot maximum height**<br>**Sheets 1 of 5, 2 of 5 and 3 of 5** |

meet the design requirements in the Statement of Work for Standard Drawing for Headwalls, USDA-NRCS Task Order 43-7442-4-1080, and Texas NRCS Conservation Practice Standard and Specifications, 578, Headwalls and other referenced codes.

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# PURPOSE

This report documents the design of three headwalls composed of timber, steel pipe piles, and cable tiebacks.

# OVERVIEW

The headwalls are briefly described as follows:

1. Headwall, maximum 6-feet high with timber cross-members, steel pipe piles, cable tiebacks, and double steel channel walers.

2. Headwall, maximum 11-feet high with timber cross-members, steel pipe piles, cable tiebacks, and double steel channel walers.

3. Headwall, maximum 16-feet high with timber cross-members, steel pipe piles, cable tiebacks, and double steel channel walers.

# SOIL PROPERTIES

The shear strength of a soil is the most important parameter when designing a headwall. The properties of soil that affect shear strength are unit weight, $\gamma$, internal friction angle, $\phi$, cohesion, $c$, and degree of saturation, $S$. The placement of granular backfill, along with spaced timbers, allows saturated soil conditions to be neglected.

The shear strength of a soil is the characteristic that controls how much vertical pressure is transferred to lateral pressure by the soil. The higher the shear strength, the less pressure is transferred laterally. Cohesive soils such as clay normally have higher shear strength than non-cohesive soils like sands and silts. The exception occurs when clay becomes wet. When clay absorbs water it loses much of its shear strength and its unit weight increases.

Parkhill, Smith & Cooper, Inc. (PSC) performed an evaluation of the soil parameters for both cohesive and non-cohesive. The results indicate that cohesive soils, specifically wet clay, control the design for this project. The properties of the wet clay designed for include: unit weight, $\gamma$, of 130 pounds per cubic foot (pcf), internal friction angle, $\phi$, of 28 degrees, and a value of 27 pound per square foot (psf) for cohesion, $c$. Highly plastic soils require special design considerations due to their expansive nature when becoming wet, as well as their tendency to cause creep. Geotechnical soil testing is required for these highly plastic soils, those soils with a Plasticity Index (PI) of 25 or greater.

# LOADS

The headwalls will undergo lateral loading resulting from the weight of the soil being supported and the surcharge from vehicle traffic and construction loads. Hydrostatic pressure loading shall be neglected because water will be allowed to flow out through spaces in headwall timbers.

## SOIL PRESSURE

The weight of the soil supported by the headwall creates a lateral loading on the wall that increases with depth. The lateral load for the soil pressure is a percentage of the vertical pressure or vertical stress, $\sigma_v$. Vertical stress in a soil is given by the equation:

$$\sigma_v = \gamma H$$

Where,

$\gamma =$ Unit weight of soil

$H =$ Depth of soil

The properties of soil cause a transfer of this vertical stress, $\sigma_v$, to a horizontal stress, $\sigma_v$. The horizontal stress is found by reducing the vertical stress by a factor. This factor is known as the coefficient of lateral earth pressure, *K*. There are three types of lateral earth pressures which have their own respective lateral earth pressure coefficients. These coefficients are:

$K_o$ : Coefficient of lateral earth pressure at rest.
$K_a$ : Coefficient of active lateral earth pressure.
$K_p$ : Coefficient of passive lateral earth pressure.

The type of deflection the soil experiences is what defines these coefficients. For this design, the deflecting soil in question is the soil nearest the headwall. $K_o$ assumes the soil has not deflected. $K_a$ assumes the soil has undergone a positive deflection; the soil has pushed the wall out away from its original position. $K_p$ assumes the soil has undergone a negative deflection; the wall pushed against or compacted the soil. For design purposes, $K_o$ is neglected. In this design, $K_a$ is used where the soil pushes against the headwall, and $K_p$ is used where the headwall pushes against the soil in the embedment.

The coefficients of active earth pressure, $K_a$, and passive earth pressure, $K_p$, can be determined using either Rankine's or Coulomb's theories. The values for these coefficients are given by the following equations:

### Non-Cohesive Soils (Coduto 2001)

$$K_a = \frac{\cos\beta - \sqrt{\cos^2\beta - \cos^2\phi}}{\cos\beta + \sqrt{\cos^2\beta - \cos^2\phi}} \left(\text{Rankine's Theory}\right)$$

$$K_a = \frac{\cos^2\left(\phi - \alpha\right)}{\cos^2\alpha\cos\left[1 + \sqrt{\frac{\sin\left(\phi + \phi_w\right)\sin\left(\phi - \beta\right)}{\cos\left(\phi_w + \alpha\right)\cos\left(\alpha - \beta\right)}}\right]^2} \left(\text{Coulomb's Theory}\right)$$

$$K_p = \frac{\cos\beta + \sqrt{\cos^2\beta - \cos^2\phi}}{\cos\beta - \sqrt{\cos^2\beta - \cos^2\phi}}$$

Where,

$\beta =$ inclination of ground surface above wall

$\phi =$ internal friction angle

$\alpha =$ inclination of wall from vertical

$\phi_w =$ wall-soil interface $= 2/3$ friction angle

### Cohesive Soils (FHWA-IF-99-015 1999)

$$K_a = \tan^2\left(45° - \frac{\phi}{2}\right) - \frac{2c}{\sigma_v}\tan^2\left(45° - \frac{\phi}{2}\right)$$

$$K_p = \tan^2\left(45° + \frac{\phi}{2}\right) + \frac{2c}{\sigma_v}\tan^2\left(45° + \frac{\phi}{2}\right)$$

Where,

$K_a =$ Coefficient of active lateral earth pressure

$K_p =$ Coefficient of passive lateral earth pressure

$\sigma_v =$ Total vertical stress

$\phi =$ effective friction angle

c = effective cohesion

(Note: In all cases $K_p$ shall be reduced by a factor of safety of 1.5.)

After determining these coefficients the lateral earth pressures acting on the wall were calculated using a linear soil pressure distribution similar to hydrostatic pressure distribution. The equation for lateral earth pressure is given by:

### Unsaturated (Coduto 2001)

$\sigma_h = K\sigma = K\gamma H$

Where,

$K$ = coefficient of lateral earth pressure

$\gamma$ = unit weight of the soil

$H$ = depth of soil

### SURCHARGE LOAD

A surcharge load acting along the ground service was assumed to act on the headwall from vehicle traffic and construction loads. A 100 psf surcharge load was assumed to act uniformly on the ground surface. This uniform load was then multiplied by the coefficient of active earth pressure, $K_a$, to obtain the pressure acting on the wall.

## DESIGN PROCEDURES

The headwall design for the Natural Resources Conservation Service (NRCS) followed the free-end design method. The design will uses an anchored cantilever design for all other cases. This design assumes the pile is rigid. Several components of the headwalls were constant through each design height. These components include: 10" steel pipe piles, embedment of 8', cable size of ¾" diameter, 2C7x9.8 walers, and 4"x12" timbers. Since most components in the design are constant the only things that vary for the different wall heights include: the number and spacing of walers with tiebacks, the spacing of the tiebacks, and spacing of the piles.

### SPACING OF PILES

Determining the pressure profile on the wall allows the calculation of the allowable spacing of the piles. For the case where one tieback is present statics can be used to find the allowable spacing of the piles. Assuming the moments about the tieback are zero creates a statically determinate problem with two unknowns. The two unknowns are the depth of embedment and the force in the tieback. Assuming moments about the tieback are zero drops out the second unknown, the force in the tieback, leaving only one unknown. Solving for the depth in this equation creates an easily solvable second order polynomial.

Wall heights with multiple levels of tiebacks create a statically indeterminate problem. A structural analysis program, RISA 2-D, was used to model a two dimensional section of the wall. To create a stable model, it was assumed that that passive soil pressure at the embedment of the pile acted as a pin at the resultant of the triangular passive pressure distribution. The tiebacks were modeled as roller connections.

### STABLILITY

It is required that soil retaining structures be able to withstand overturning failure and sliding failure with a factor of safety of at least 1.5 for each. In this design the cable tiebacks restrain the wall from overturning while the embedment prevents sliding. Each stability check was made in the calculations (see appendix) with each exceeding the required factor of safety.

### PILE DESIGN

Once the loadings were determined, the capacity of the steel pipe pile was checked. This design included determining the maximum stress in the pipe for both bending and shear. The yield stress of the steel was assumed to be 36 ksi and the design used the ASD steel construction manual to design the members.

### TIMBER DESIGN

The design of the timber members included factors such as bending, shear, and bearing. Deflection was not considered in this design since serviceability is not an issue related to headwall design. The bending stress in the member was checked at the base of the headwall where the greatest pressure would be present. The "National Design Specification for Wood Construction" was used to determine the maximum bending stress and the maximum shear stress in the wood. This bending stress was then multiplied by design value adjustment factors. These factors include a repetitive member factor, CR, a wet service factor, CM, a flat use factor, CFU, a size factor, CF, and a shear stress factor, CH. A design value of 825 psi was used for the maximum bending stress and 95 psi for the maximum shear stress.

## ASSUMPTIONS

Free-end design method assumes the pile is rigid and rotates about the tieback or the top of the wall. The free-end design method assumes the soil pressure is in an active state above the base of retaining wall. Below the bottom of the retaining wall, the pressure is assumed to be in a passive state. It was assumed that saturated conditions would not be present in the soil behind the retaining wall because excess water would be able to flow out between the timbers in the wall.

The active soil pressures were calculated using Rankine's Theory for Soils which assumes: (Coduto, 2001)

1. The soil is homogeneous and isotropic, which means, $c$, $\phi$, and $\gamma$ have the same values everywhere, and they have same values in all directions at every point.

2. The most critical shear surface is a plane.

3. The ground surface is a plane, although it does not necessarily need to be level.

4. The wall is infinitely long so that the problem may be analyzed in only two dimensions.

5. The resultant of the normal and shear forces that act on the back of the wall is inclined at an angle parallel to the ground service.

It was assumed the worst loading case for the headwall design would be that of wet clay. When clay becomes wet it absorbs water which increases its unit weight. The friction angle, $\phi$, for clay is smaller which equates to a larger value for $K_a$. The combination of these variable results in a greater lateral load imparted on the wall.

# BILL OF MATERIALS

### 6 FT HEADWALL

| Max 6' Headwall | | | | Height = ft |
|---|---|---|---|---|
| | Quantity | Unit | Total Quantity | Length = ft |
| 10" Pipe | 0.700 | lf | | |
| 4x8 Timbers | 1.600 | lf | | |
| 3/4" Cable | 0.517 | lf | | |
| C7x9.8 | 0.333 | lf | | |
| 1/2" Dia Bolts | 0.133 | ea | | |
| 10 GA Screws | 1.000 | ea | | |
| Lock Washers | 0.150 | ea | | |
| 3/4" Dia Bolts | 0.150 | ea | | |
| 1/2 Plate | 0.004 | sf | | |
| 1"x30" Eye Bolts | 0.025 | ea | | |
| Cable Clamps | 0.033 | ea | | |

(Note: all units are per linear foot of wall per unit height of wall)

### 11 FT HEADWALL

| Max 11' Headwall | | | | Height = ft |
|---|---|---|---|---|
| | Quantity | Unit | Total Quantity | Length = ft |
| 10" Pipe | 0.518 | lf | | |
| 4x8 Timbers | 1.600 | lf | | |
| 3/4" Cable | 1.691 | lf | | |
| C7x9.8 | 0.364 | lf | | |
| 1/2" Dia Bolts | 0.145 | ea | | |
| 10 GA Screws | 1.000 | ea | | |
| Lock Washers | 0.136 | ea | | |
| 3/4" Dia Bolts | 0.136 | ea | | |
| 1/2 Plate | 0.005 | sf | | |
| 1"x30" Eye Bolts | 0.018 | ea | | |
| Cable Clamps | 0.036 | ea | | |

(Note: all units are per linear foot of wall per unit height of wall)

### 16 FT HEADWALL

| Max 16' Headwall | | | | Height = ft |
|---|---|---|---|---|
| | Quantity | Unit | Total Quantity | Length = ft |
| 10" Pipe | 0.750 | lf | | |
| 4x8 Timbers | 1.600 | lf | | |
| 3/4" Cable | 2.906 | lf | | |
| C7x9.8 | 0.375 | lf | | |
| 1/2" Dia Bolts | 0.250 | ea | | |
| 10 GA Screws | 1.615 | ea | | |
| Lock Washers | 0.250 | ea | | |
| 3/4" Dia Bolts | 0.250 | ea | | |
| 1/2 Plate | 0.016 | sf | | |
| 1"x30" Eye Bolts | 0.063 | ea | | |
| Cable Clamps | 0.063 | ea | | |

(Note: all units are per linear foot of wall per unit height of wall)

# REFERENCES

1. Coduto, Donald P., *Foundation Design: Principle and Practices,* Second Edition, Prentice Hall, Upper Saddle River, New Jersey, 2001

2. Coduto, Donald P., *Geotechnical Engineering Principles and Practices*, Prentice Hall, Upper Saddle River, New Jersey, 1999

3. U.S. Department of Agriculture Soil Conservation Service Engineering, *Technical release Number 74: Lateral Earth Pressure*, U.S. Department of Agriculture Soil Conservation Service Engineering, 1989

4. American Wood Council, *Supplement NDS National Design Specification For Wood Construction*, American Forest & Paper Association, 1997

5. American Institute of Steel Construction, Inc., *Manual of Steel Construction – Allowable Stress Design,* Ninth Edition, Chicago, Illinois, 1989

6. Terzaghi, Karl and Peck, Ralph B. *Soil Mechanics in Engineering Practice*, John Wiley, New York, 1964

7. Sabatini, Pass, and Bachus, *Geotechnical Engineering Circular No. 4 – Ground Anchors and Anchored Systems,* Publication No. FHWA-IF-99-0153, 1999

8. The Crosby Group, Inc., *Blocks & Fittings for Wire Rope & Chain – General Catalog,* 1992

9. Lift-All, *Catalog '98*, 1997

10. ASTM International, *ASTM Standards in Building Codes*, Forty-first Edition, 2004

# APPENDIX A

# STATEMENT OF WORK

# STATEMENT OF WORK
# STANDARD DRAWINGS – HEADWALLS
# CONSERVATION PRACTICE STANDARD 578

**These deliverables apply to this specific Statement of Work. All engineering drawings and designs shall be sealed by a Professional Engineer licensed to practice engineering in Texas. All documentation provided to the local NRCS contact shall be generated in *.doc, *.pdf, *.dwg, or *.xls format and provided on CD media.**

## DESIGN

### Deliverables:

1. Structural design report and 3 Headwall Standard Drawings that meet current NRCS Standards; AISC, ASD; NDS, ASD; and ACI concrete design criteria and installation requirements. Construction and material specifications shall be included on the standard drawings for.
    a. Headwall, timber and steel sheet piling, Maximum 6-ft high, with timber and steel pipe piles, tiebacks and anchors if needed.
    b. Headwall, timber and steel sheet piling, Maximum 11-ft high, with timber and steel pipe piles, tiebacks and anchors.
    c. Headwall, timber and steel sheet piling, Maximum 16-ft high, with timber and steel pipe piles, tiebacks and anchors.
2. Design shall be signed and sealed by a licensed professional engineer, licensed to practice in Texas, certifying that all components comply with the design requirements set forth in this Statement of Work, Texas NRCS Conservation Practice Standard 587, Structure for Water Control, and other referenced codes.
3. Drawings shall include construction notes and address potential erosion around and downstream of the structure. A provision for optional placement of rock rip rap, with appropriate foundation preparation, and material and construction specifications from National Engineering Handbook, Part 642, Chapter 2 (NEM 642-2), shall be shown on the drawings. Adequate sections and details to clearly indicate installation of connectors, openings for culverts and pipes, and excavation and backfill requirements
4. Structures shall be designed for the materials listed in (1) above. Design pile load conditions shall include foundations in both cohesive and non-cohesive soils. TR-74, Lateral Earth Pressures, shall be used to determine wall, whale, and connection loading. Drainage features shall be designed for soil backfill materials with more than 15% fines and for all wall heights greater than 11-ft. Drawings and specifications shall require geotechnical testing and recommendations on wall heights greater than 11-ft, or less if highly plastic soils are present on lesser heights. Piling and drainage construction details shall be shall be shown on the drawings and referenced to appropriate specifications as necessary.
6. Tiebacks and anchor requirements shall be designed for placement in backfill materials and in-situ soils next to roads and highways. Tiebacks and anchors shall be located to not disturb existing roads or highways. Drawings shall specify testing of tiebacks and anchors for compliance with required strengths. Required strength shall be stated on the drawings.

# STATEMENT OF WORK
# STANDARD DRAWINGS – HEADWALLS
# CONSERVATION PRACTICE STANDARD 578

7 Reinforced concrete design, if required, shall comply with ACI 350-01 and NRCS Technical Release 67, Reinforced Concrete Strength Design. Steel members and connectors shall comply with American Institute of Steel Construction, Manual of Steel Construction, Allowable Stress Design. Timber members, connectors, and piles shall comply with the American Institute of Timber Construction and the National Design Standards for Wood Construction (NDS).

8. The designer shall provide for each drawing the following:

   a. Design Report to include a detailed presentation of the design procedure, assumptions, design criteria, loads and load combinations, design computations, critical load combination(s) for the various elements of the structure, design limitations, and specific requirements for connections, materials, embedment, anchors, tiebacks, and other unusual situations.

   b. A bill of materials, per unit width of a section, for unit heights up to 6-ft, 11-ft, and 16-ft shall be provided expressed in linear feet per unit of height, number and size of connectors and hardware per unit of height, or cu yd for drain materials per unit of height. .

   c. Construction specifications and notes to clearly describe the work and installation requirements, safety requirements, pile installation and driving requirements, detail instructions for underground utilities, maximum excavated cut slopes, testing tiebacks and anchors, and geotechnical investigation, testing, and recommendations.

   d. Provide five sets of 11" X 17" construction drawings, one electronic file copy in PDF format (Adobe Acrobat) of the construction drawing details and specifications, and one electronic file copy in DWG format (AutoCad) of the construction drawing details and specifications.

## REFERENCES

- Texas, NRCS Field Office Technical Guide (eFOTG), Section IV, Conservation Practice Standard – Structure for Water Control, 578 http://www.nrcs.gov/technical/efotg/.
- NRCS National Engineering Manual (NEM).
- Technical Release 74, Lateral Earth Pressures
- ACI 350-01, AISI, NDS
- Additional information needed should be requested from the NRCS COTR.
- NRCS, National Engineering Handbook, Part 642, Chapter 2. CS027 (Drain Fill), CS095 (Geotextile), CS013 (Piling), etc.

# APPENDIX B

# DESIGN CALCULATIONS

# Parkhill, Smith & Cooper, Inc.

**Engineers ▪ Architects ▪ Planners**

## Headwall Design Calculations

Maximum 6' High Headwall
1 Waler with 1 Tieback Every 2 Bays
Piles Spaced at 5'

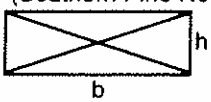
**Date :** 11/1/2006
**PSC Job No. :** 01-2926-04

### Pile Properties

| | | |
|---|---|---|
| B = | 10 in. | (Outside Diameter of Pile) |
| t = | 0.34 in. | (Pile Thickness) |
| $f_y$ = | 36 ksi | (Yield Strength of Steel) |
| S = | 5 ft | (Pile Spacing) |
| D = | 8 ft | (Embedment Depth) |

### Timber Properties

| | | |
|---|---|---|
| $f_b$ = | 1200 psi | (Southern Pine No. 2 Grade) |
| $f_v$ = | 175 psi | |
| b = | 7.5 in | |
| h = | 3.5 in | |




### Headwall Properties

| | | |
|---|---|---|
| H = | 6 ft | (height of wall) |
| $D_{tieback}$ | 3 ft | (depth to tieback) |
| $\alpha$ = | 0 ° | (inclination of wall from vertical) |

### Soil Properties

| | | |
|---|---|---|
| $\gamma_{soil}$ = | 130 lb/ft$^3$ | (unit weight of soil above ground water table) |
| c = | 27 lb/ft$^2$ | (cohesion) |
| q = | 100 lb/ft$^2$ | (surcharge pressure) |
| $\beta$ = | 2 ° | (inclination of ground surface above the wall) |
| $\phi'$ = | 28 ° | (effective friction angle) |
| $K_a$ = | 0.35 | (coefficient of active soil pressure) |
| $K_p$ = | 2 | (coefficient of passive soil pressure) |

$$K_a = \tan^2\left(45° - \frac{\phi'}{2}\right) - \frac{2c'}{\sigma'_v}\tan^2\left(45° - \frac{\phi'}{2}\right)$$

$$K_p = \tan^2\left(45° + \frac{\phi'}{2}\right) + \frac{2c'}{\sigma'_v}\tan^2\left(45° + \frac{\phi'}{2}\right)$$

Where,

$K_a$ = Coefficient of active lateral earth pressure

$K_p$ = Coefficient of passive lateral earth pressure

c = Cohesion

$\sigma_v$ = Total vertical stress

$\phi$ = Friction angle

## Check Sliding

| Area | $F_{resultant}$ (lb) | $D_{arm}$ (ft) | $M_{tieback}$ (ft-lb) |
|---|---|---|---|
| 1 | 525 | 1.5 | 788 |
| 2 | 1024 | 1.0 | 1024 |
| 3 | 525 | -1.5 | -788 |
| 4 | 2048 | -1.5 | -3071 |
| 5 | 1024 | -2.0 | -2048 |
| 6 | 233 | -7.0 | -1633 |
| 7 | 1820 | -7.0 | -12740 |
| 8 | 1213 | -8.3 | -10111 |
| 9 | 6933 | 8.3 | 57778 |
| | | Sum of Moments = | 29198 |

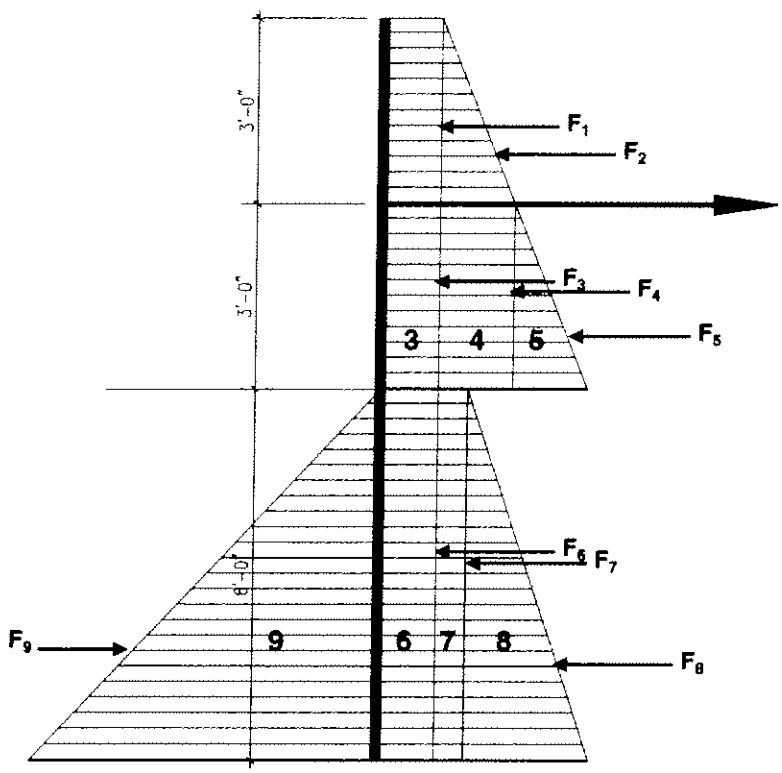
$$\text{Factor of Safety} = \frac{\Sigma M_{resisting}}{\Sigma M_{overturning}}$$

Factor of Safety = 2.0

Minimum Factor of Safety = 1.5

OK

Max Lateral Pressure on Wall (psf) = 308



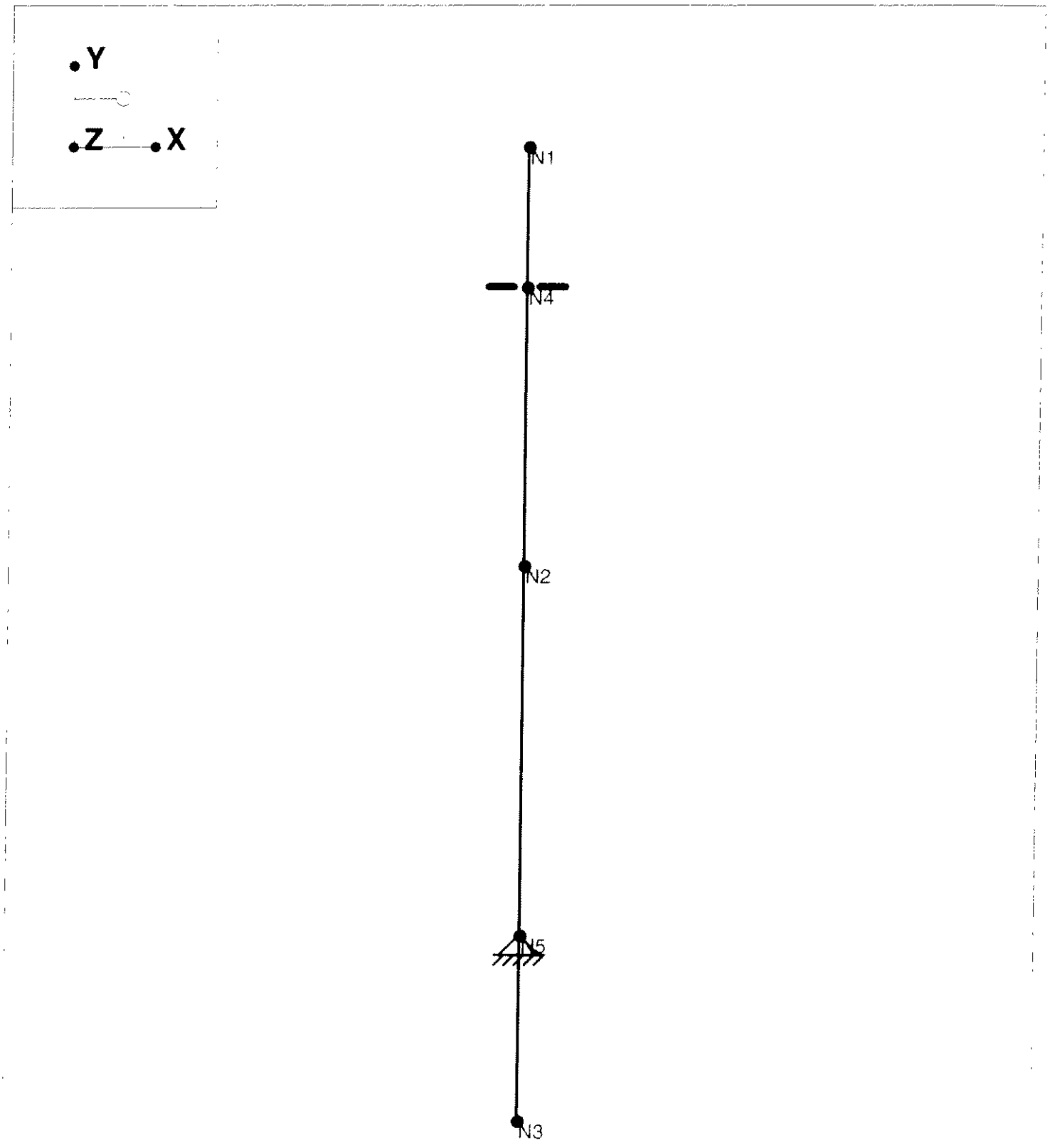

## Check Overturning

$P_{tieback}$ = 4,449 lb OK Factor of Safety = 3.3

## Determine Max Moment in Pile

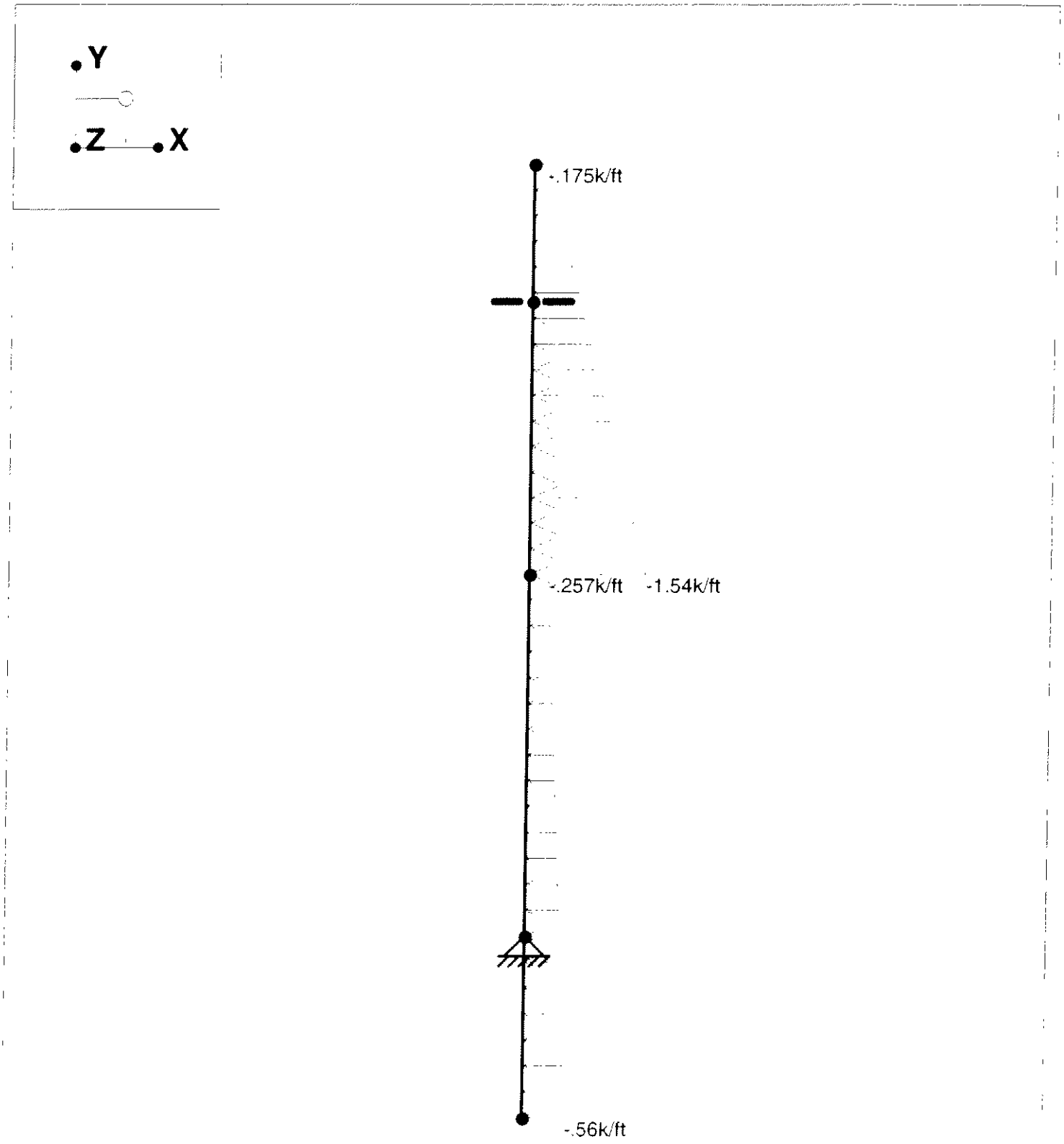
$M_{max}$ = 6,600 ft-lb

| | | | |
|---|---|---|---|
| **Pile Design** | | | |
| With Tieback | | | |
| A = | 10.32 $in^2$ | | |
| I = | 120.51 $in^4$ | | |
| S = | 24.10 $in^3$ | | |
| $f_b$ = | 23.76 ksi | | |
| $M_{total}$ = | 6.60 ft-k | OK | |
| $M_{allowable}$ = | 47.72 ft-k | | |
| **Cable Design - 3/4" Diameter Cable** | | | |
| Breaking Strength = | 58,800 lb | | |
| Factor of Safety = | 3 | | |
| Allowable Load = | 19,600 lb | | |
| Allowable Load per wall = | 9,800 lb | | |
| Allowable Load per bay = | 4,900 lb | OK | |
| **Timber Design** | | | |
| A = | 26.25 $in^2$ | | |
| I = | 26.80 $in^4$ | | |
| S = | 15.31 $in^3$ | | $f_v = \frac{3V_{max}}{2bd}$ |
| $f_b$ = | 1407.60 psi | | |
| $M_{total}$ = | 601.56 ft-lb | OK | $F'_{v(allowable)} = F_v C_R C_M C_F$ |
| $M_{allowable}$ = | 1796.16 ft-lb | | |
| $f_v$ = | 27.50 psi | OK | Where, |
| $F'_{v(allowable)}$ = | 203.7 psi | | $F'_v$ = Adjusted allowable shear stress |
| | | | $C_{R,M,F}$ = Wood Modification Factors |
| **Whaler Design (for tieback)** | | | |
| $F_b$ = | 23.76 ksi | | |
| $S_{x(req)}$ = | 5.62 $in^3$ | 2C7x9.8 | $S_{x(req)} = \frac{M_{max}}{F_b}$ |
| $S_x$ = | 12.14 $in^3$ | | |
| $M_{total}$ = | 11.1 ft-lb | | |
| $M_{allowable}$ = | 24.0 ft-lb | OK | |




Results for LC 1, Design

| | | |
|---|---|---|
| Parkhill, Smith & Cooper | NRCS 6' Headwall | |
| Matt Laverty | | Oct 31, 2006 at 11:15 PM |
| 2926.04 | | 6 foot wall.r2d |




Loads: LC 1, Design
Results for LC 1, Design

| | | |
|---|---|---|
| Parkhill, Smith & Cooper | NRCS 6' Headwall | |
| Matt Laverty | | Oct 31, 2006 at 11:14 PM |
| 2926.04 | | 6 foot wall.r2d |

## Basic Load Cases

| | BLC Description | Category | X Gravity | Y Gravity | Joint | Point | Distributed |
|---|---|---|---|---|---|---|---|
| 1 | Surcharge (wall) | None | | | | | 1 |
| 2 | Surcharge (pile) | None | | | | | 1 |
| 3 | Soil (wall) | None | | | | | 1 |
| 4 | Soil (pile) | None | | | | | 1 |

## Joint Boundary Conditions

| | Joint Label | X [k/in] | Y [k/in] | Rotation[k-ft/rad] | Footing |
|---|---|---|---|---|---|
| 1 | N4 | Reaction | | | |
| 2 | N5 | Reaction | Reaction | | |

## Joint Coordinates and Temperatures

| | Label | X [ft] | Y [ft] | Temp [F] |
|---|---|---|---|---|
| 1 | N1 | 0 | 14 | 0 |
| 2 | N2 | 0 | 8 | 0 |
| 3 | N3 | 0 | 0 | 0 |
| 4 | N4 | 0 | 12 | 0 |
| 5 | N5 | 0 | 2.667 | 0 |

## Joint Reactions (By Combination)

| | LC | Joint Label | X [k] | Y [k] | MZ [k-ft] |
|---|---|---|---|---|---|
| 1 | 1 | N4 | 4.449 | 0 | 0 |
| 2 | 1 | N5 | 3.964 | 0 | 0 |
| 3 | 1 | Totals: | 8.413 | 0 | |
| 4 | 1 | COG (ft): | NC | NC | |

## Load Combinations

| | Description | Solve | PD... | SR... | BLC | Factor | BLC | Factor | BLC | Factor | BLC | Factor | BLC | Factor | BLC | Factor | BLC | Factor | BLC | Factor |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Design | Yes | | | 1 | 5 | 2 | 1 | 3 | 5 | 4 | 1 | | | | | | | | |

## Member Distributed Loads (BLC 1 : Surcharge (wall))

| | Member Label | Direction | Start Magnitude[k/ft,d... | End Magnitude[k/ft,d... | Start Location[ft,%] | End Location[ft,%] |
|---|---|---|---|---|---|---|
| 1 | M2 | X | -.035 | -.035 | 0 | 0 |

## Member Distributed Loads (BLC 2 : Surcharge (pile))

| | Member Label | Direction | Start Magnitude[k/ft,d... | End Magnitude[k/ft,d... | Start Location[ft,%] | End Location[ft,%] |
|---|---|---|---|---|---|---|
| 1 | M1 | X | -.03 | -.03 | 0 | 0 |

## Member Distributed Loads (BLC 3 : Soil (wall))

| | Member Label | Direction | Start Magnitude[k/ft,d... | End Magnitude[k/ft,d... | Start Location[ft,%] | End Location[ft,%] |
|---|---|---|---|---|---|---|
| 1 | M2 | X | -.273 | 0 | 0 | 0 |

## Member Distributed Loads (BLC 4 : Soil (pile))

| | Member Label | Direction | Start Magnitude[k/ft,d... | End Magnitude[k/ft,d... | Start Location[ft,%] | End Location[ft,%] |
|---|---|---|---|---|---|---|
| 1 | M1 | X | -.53 | -.227 | 0 | 0 |

## *Member Section Forces*

| | LC | Member Label | Sec | Axial[k] | Shear[k] | Moment[k-ft] |
|---|---|---|---|---|---|---|
| 1 | 1 | M1 | 1 | 0 | 0 | 0 |
| 2 | | | 2 | 0 | 1.044 | -1.07 |
| 3 | | | 3 | 0 | -2.027 | 1.209 |
| 4 | | | 4 | 0 | -1.286 | 4.497 |
| 5 | | | 5 | 0 | -.696 | 6.454 |
| 6 | 1 | M2 | 1 | 0 | -.696 | 6.454 |
| 7 | | | 2 | 0 | 1.358 | 5.894 |
| 8 | | | 3 | 0 | 2.9 | 2.637 |
| 9 | | | 4 | 0 | -.518 | -.325 |
| 10 | | | 5 | 0 | 0 | 0 |

# Parkhill, Smith & Cooper, Inc.

**Engineers ▪ Architects ▪ Planners**

## Headwall Design Calculations

Maximum 11' High Headwall
2 Walers with 1 Tieback per Bay
Piles Spaced at 5'

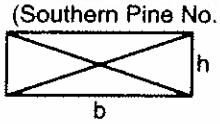
**Date :** 11/1/2006
**PSC Job No. :** 01-2926-04

### Pile Properties

| | | |
|---|---|---|
| B = | 10 in. | (Outside Diameter of Pile) |
| t = | 0.34 in. | (Pile Thickness) |
| $f_y$ = | 36 ksi | (Yield Strength of Steel) |
| S = | 5 ft | (Pile Spacing) |
| D = | 8 ft | (Embedment Depth) |

### Timber Properties

| | | |
|---|---|---|
| $f_b$ = | 1200 psi | (Southern Pine No. 2 Grade) |
| $f_v$ = | 175 psi | |
| b = | 7.5 in | |
| h = | 3.5 in | |




### Headwall Properties

| | | |
|---|---|---|
| H = | 11 ft | (height of wall) |
| $\alpha$ = | 0 ° | (inclination of wall from vertical) |

### Soil Properties

| | | |
|---|---|---|
| $\gamma_{soil}$ = | 130 lb/ft$^3$ | (unit weight of soil above ground water table) |
| c = | 27 lb/ft$^2$ | (cohesion) |
| q = | 100 lb/ft$^2$ | (surcharge pressure) |
| $\beta$ = | 2 ° | (inclination of ground surface above the wall) |
| $\phi'$ = | 28 ° | (effective friction angle) |
| $K_a$ = | 0.35 | (coefficient of active soil pressure) |
| $K_p$ = | 2 | (coefficient of passive soil pressure) |

$$K_a = \tan^2\left(45° - \frac{\phi'}{2}\right) - \frac{2c'}{\sigma'_v}\tan^2\left(45° - \frac{\phi'}{2}\right)$$

$$K_p = \tan^2\left(45° + \frac{\phi'}{2}\right) + \frac{2c'}{\sigma'_v}\tan^2\left(45° + \frac{\phi'}{2}\right)$$

Where,

$K_a$ = Coefficient of active lateral earth pressure

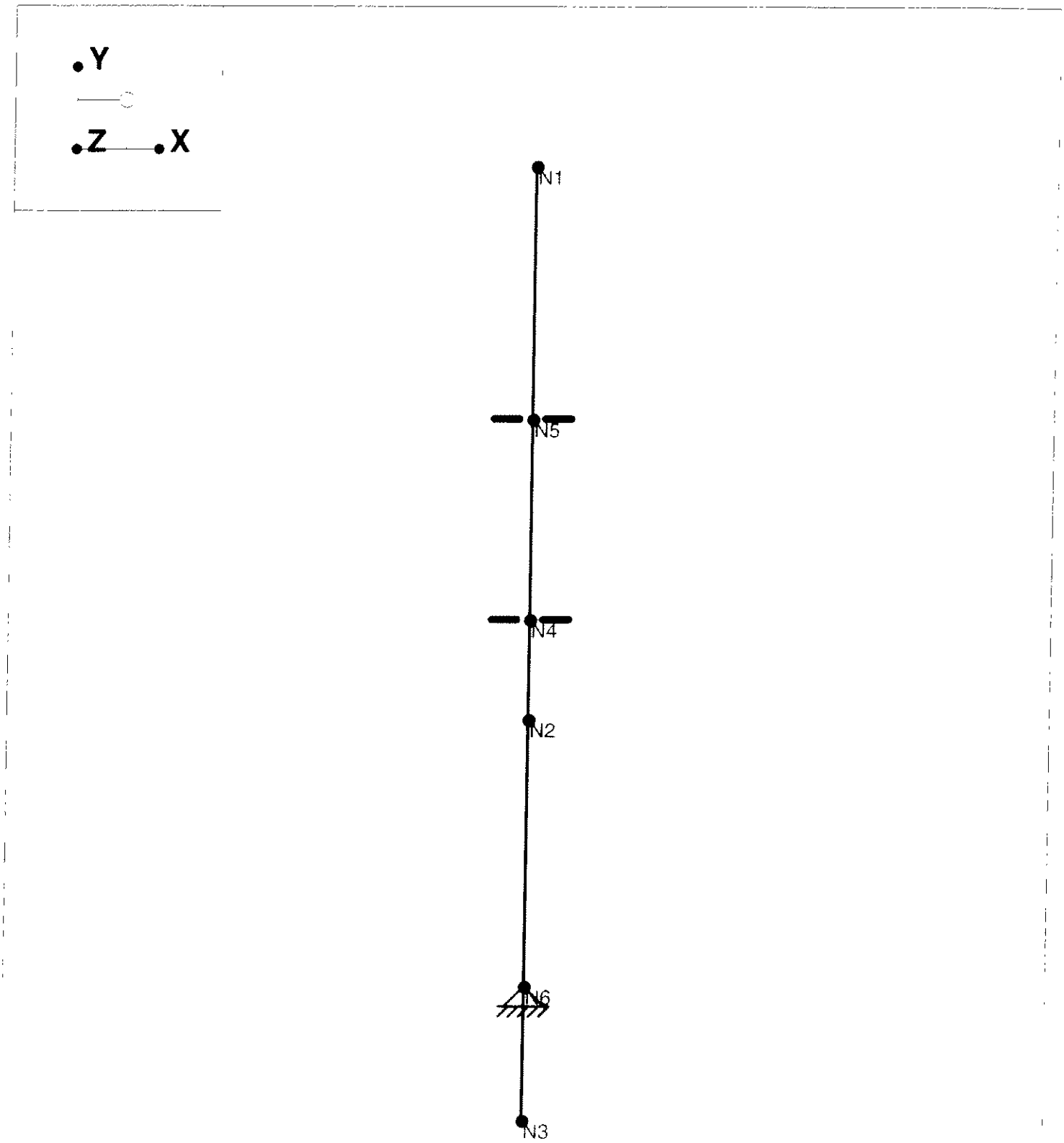
$K_p$ = Coefficient of passive lateral earth pressure

c = Cohesion

$\sigma_v$ = Total vertical stress

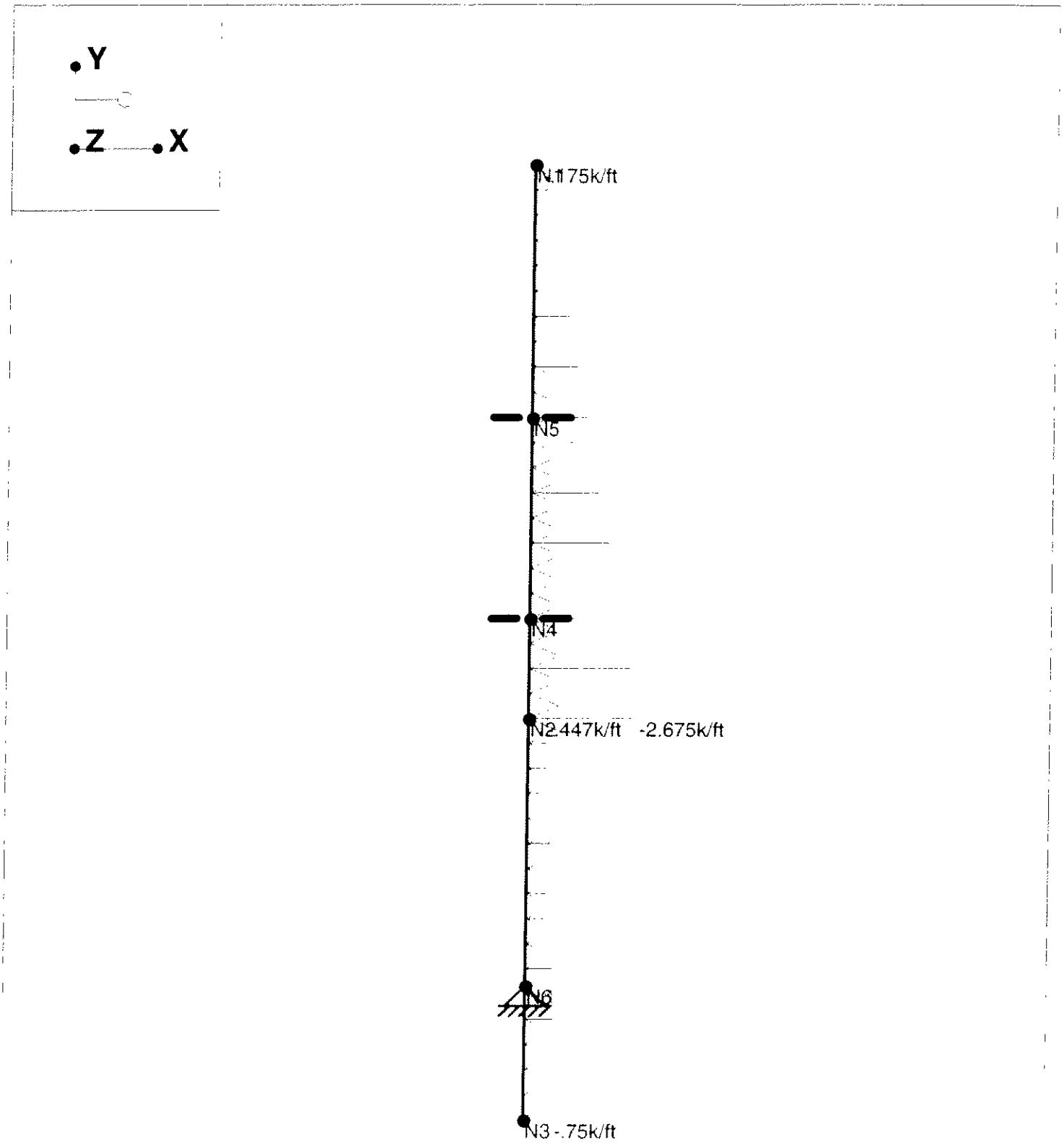
$\phi$ = Friction angle

| | | | | |
|---|---|---|---|---|
| **Check Sliding** | | | | |
| Reaction at Embedment = | 4342 lb | OK | | |
| Allowable Reaction = | 4622 lb | | | |
| Factor of Safety = | 1.6 | (Minimum FOS = 1.5) | | |
| **Check Overturning** | | | | |
| $P_{tieback(top)}$ = | 7,788 lb | OK | Factor of Safety = | 3.8 |
| $P_{tieback(bottom)}$ = | 8,332 lb | OK | Factor of Safety = | 3.5 |
| | | | (Minimum FOS = 1.5) | |
| **Determine Max Moment in Pile** | | | | |
| $M_{max}$ = | 6,800 ft-lb | | | |
| **Pile Design** | | | | |
| A = | 10.32 $in^2$ | | | |
| I = | 120.51 $in^4$ | | | |
| S = | 24.10 $in^3$ | | | |
| $f_b$ = | 23.76 ksi | | | |
| $M_{total}$ = | 6.80 ft-k | OK | | |
| $M_{allowable}$ = | 47.72 ft-k | | | |
| **Cable Design - 3/4" Diameter Cable** | | | | |
| Breaking Strength = | 58,800 lb | | | |
| Factor of Safety = | 3 | | | |
| Allowable Load = | 19,600 lb | | | |
| Allowable Load per wall = | 9,800 lb | | | |
| Allowable Load per bay = | 9,800 lb | | | |
| **Timber Design** | | | | |
| A = | 26.25 $in^2$ | | | |
| I = | 26.80 $in^4$ | | | |
| S = | 15.31 $in^3$ | | $f_v = \frac{3V_{max}}{2bd}$ | |
| $f_b$ = | 1407.60 psi | | | |
| $M_{total}$ = | 1045.90 ft-lb | OK | $F'_{v(allowable)} = F_v C_R C_M C_F$ | |
| $M_{allowable}$ = | 1796.16 ft-lb | | | |
| $f_v$ = | 47.81 psi | OK | Where, | |
| $F'_{v(allowable)}$ = | 203.7 psi | | $F'_v$ = Adjusted allowable shear stress | |
| | | | $C_{R,M,F}$ = Wood Modification Factors | |
| **Whaler Design (for tieback)** | | | | |
| $F_b$ = | 23.76 ksi | | | |
| $S_{x(req)}$ = | 9.83 $in^3$ | 2C7x9.8 | $S_{x(req)} = \frac{M_{max}}{F_b}$ | |
| $S_x$ = | 12.14 $in^3$ | | | |
| $M_{total}$ = | 20.8 ft-lb | | | |
| $M_{allowable}$ = | 24.0 ft-lb | OK | | |




Results for LC 1, Design

| | | |
|---|---|---|
| Parkhill, Smith & Cooper | NRCS 11' Headwall | |
| Matt Laverty | | Oct 31, 2006 at 11:16 PM |
| 2926.04 | | 11 foot wall.r2d |




Loads: LC 1, Design
Results for LC 1, Design

| | | |
|---|---|---|
| Parkhill, Smith & Cooper | NRCS 11' Headwall | |
| Matt Laverty | | Oct 31, 2006 at 11:16 PM |
| 2926.04 | | 11 foot wall.r2d |

## Basic Load Cases

| | BLC Description | Category | X Gravity | Y Gravity | Joint | Point | Distributed |
|---|---|---|---|---|---|---|---|
| 1 | Surcharge (wall) | None | | | | | 1 |
| 2 | Surcharge (pile) | None | | | | | 1 |
| 3 | Soil (wall) | None | | | | | 1 |
| 4 | Soil (pile) | None | | | | | 1 |

## Joint Boundary Conditions

| | Joint Label | X [k/in] | Y [k/in] | Rotation[k-ft/rad] | Footing |
|---|---|---|---|---|---|
| 1 | N4 | Reaction | | | |
| 2 | N5 | Reaction | | | |
| 3 | N6 | Reaction | Reaction | | |

## Joint Coordinates and Temperatures

| | Label | X [ft] | Y [ft] | Temp [F] |
|---|---|---|---|---|
| 1 | N1 | 0 | 19 | 0 |
| 2 | N2 | 0 | 8 | 0 |
| 3 | N3 | 0 | 0 | 0 |
| 4 | N4 | 0 | 10 | 0 |
| 5 | N5 | 0 | 14 | 0 |
| 6 | N6 | 0 | 2.667 | 0 |

## Joint Reactions

| | LC | Joint Label | X [k] | Y [k] | MZ [k-ft] |
|---|---|---|---|---|---|
| 1 | 1 | N4 | 8.332 | 0 | 0 |
| 2 | 1 | N5 | 7.788 | 0 | 0 |
| 3 | 1 | N6 | 4.342 | 0 | 0 |
| 4 | 1 | Totals: | 20.463 | 0 | |
| 5 | 1 | COG (ft): | NC | NC | |

## Load Combinations

| | Description | Solve | PD... | SR... | BLC | Factor | BLC | Factor | BLC | Factor | BLC | Factor | BLC | Factor | BLC | Factor | BLC | Factor | BLC | Factor |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Design | Yes | | | 1 | 5 | 2 | 1 | 3 | 5 | 4 | 1 | | | | | | | | |

## Member Distributed Loads (BLC 1 : Surcharge (wall))

| | Member Label | Direction | Start Magnitude[k/ft,d... | End Magnitude[k/ft,d... | Start Location[ft,%] | End Location[ft,%] |
|---|---|---|---|---|---|---|
| 1 | M2 | X | -.035 | -.035 | 0 | 0 |

## Member Distributed Loads (BLC 2 : Surcharge (pile))

| | Member Label | Direction | Start Magnitude[k/ft,d... | End Magnitude[k/ft,d... | Start Location[ft,%] | End Location[ft,%] |
|---|---|---|---|---|---|---|
| 1 | M1 | X | -.03 | -.03 | 0 | 0 |

## Member Distributed Loads (BLC 3 : Soil (wall))

| | Member Label | Direction | Start Magnitude[k/ft,d... | End Magnitude[k/ft,d... | Start Location[ft,%] | End Location[ft,%] |
|---|---|---|---|---|---|---|
| 1 | M2 | X | -.5 | 0 | 0 | 0 |

## Member Distributed Loads (BLC 4 : Soil (pile))

| | Member Label | Direction | Start Magnitude[k/ft,d... | End Magnitude[k/ft,d... | Start Location[ft,%] | End Location[ft,%] |
|---|---|---|---|---|---|---|
| 1 | M1 | X | -.72 | -.417 | 0 | 0 |

## *Member Section Forces*

| | LC | Member Label | Sec | Axial[k] | Shear[k] | Moment[k-ft] |
|---|---|---|---|---|---|---|
| 1 | 1 | M1 | 1 | 0 | 0 | 0 |
| 2 | | | 2 | 0 | 1.424 | -1.45 |
| 3 | | | 3 | 0 | -1.645 | .192 |
| 4 | | | 4 | 0 | -.524 | 2.337 |
| 5 | | | 5 | 0 | .446 | 2.39 |
| 6 | 1 | M2 | 1 | 0 | .446 | 2.39 |
| 7 | | | 2 | 0 | -1.39 | -1.913 |
| 8 | | | 3 | 0 | 3.388 | -5.055 |
| 9 | | | 4 | 0 | -1.341 | -1.45 |
| 10 | | | 5 | 0 | 0 | 0 |

# Parkhill, Smith & Cooper, Inc.

**Engineers ▪ Architects ▪ Planners**

## Headwall Design Calculations

Maximum 16' High Headwall
3 Walers with 1 Tieback per Bay
Piles Spaced at 3'

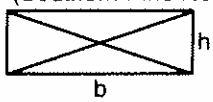
**Date :** 11/1/2006
**PSC Job No. :** 01-2926-04

### Pile Properties

| | | |
|---|---|---|
| B = | 10 in. | (Outside Diameter of Pile) |
| t = | 0.34 in. | (Pile Thickness) |
| $f_y$ = | 36 ksi | (Yield Strength of Steel) |
| S = | 3 ft | (Pile Spacing) |
| D = | 8 ft | (Embedment Depth) |

### Timber Properties

| | | |
|---|---|---|
| $f_b$ = | 1200 psi | (Southern Pine No. 2 Grade) |
| $f_v$ = | 175 psi | |
| b = | 7.5 in | |
| h = | 3.5 in | |




### Headwall Properties

| | | |
|---|---|---|
| H = | 16 ft | (height of wall) |
| $\alpha$ = | 0 ° | (inclination of wall from vertical) |

### Soil Properties

| | | |
|---|---|---|
| $\gamma_{soil}$ = | 130 lb/ft$^3$ | (unit weight of soil above ground water table) |
| c = | 27 lb/ft$^2$ | (cohesion) |
| q = | 100 lb/ft$^2$ | (surcharge pressure) |
| $\beta$ = | 2 ° | (inclination of ground surface above the wall) |
| $\phi'$ = | 28 ° | (effective friction angle) |
| $K_a$ = | 0.35 | (coefficient of active soil pressure) |
| $K_p$ = | 2 | (coefficient of passive soil pressure) |

$$K_a = \tan^2\left(45° - \frac{\phi'}{2}\right) - \frac{2c'}{\sigma'_v}\tan^2\left(45° - \frac{\phi'}{2}\right)$$

$$K_p = \tan^2\left(45° + \frac{\phi'}{2}\right) + \frac{2c'}{\sigma'_v}\tan^2\left(45° + \frac{\phi'}{2}\right)$$

Where,

$K_a$ = Coefficient of active lateral earth pressure

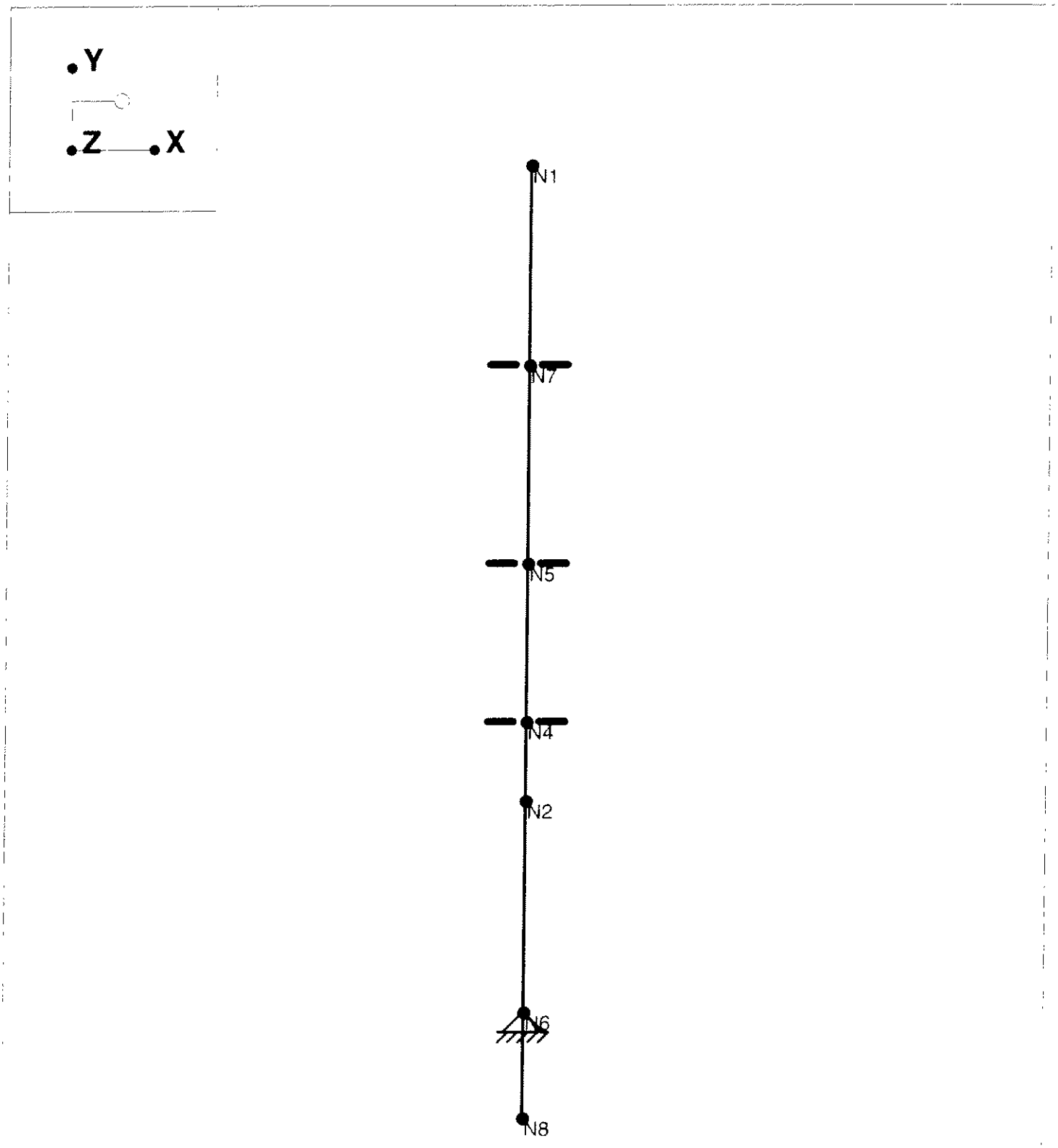
$K_p$ = Coefficient of passive lateral earth pressure

c = Cohesion

$\sigma_v$ = Total vertical stress

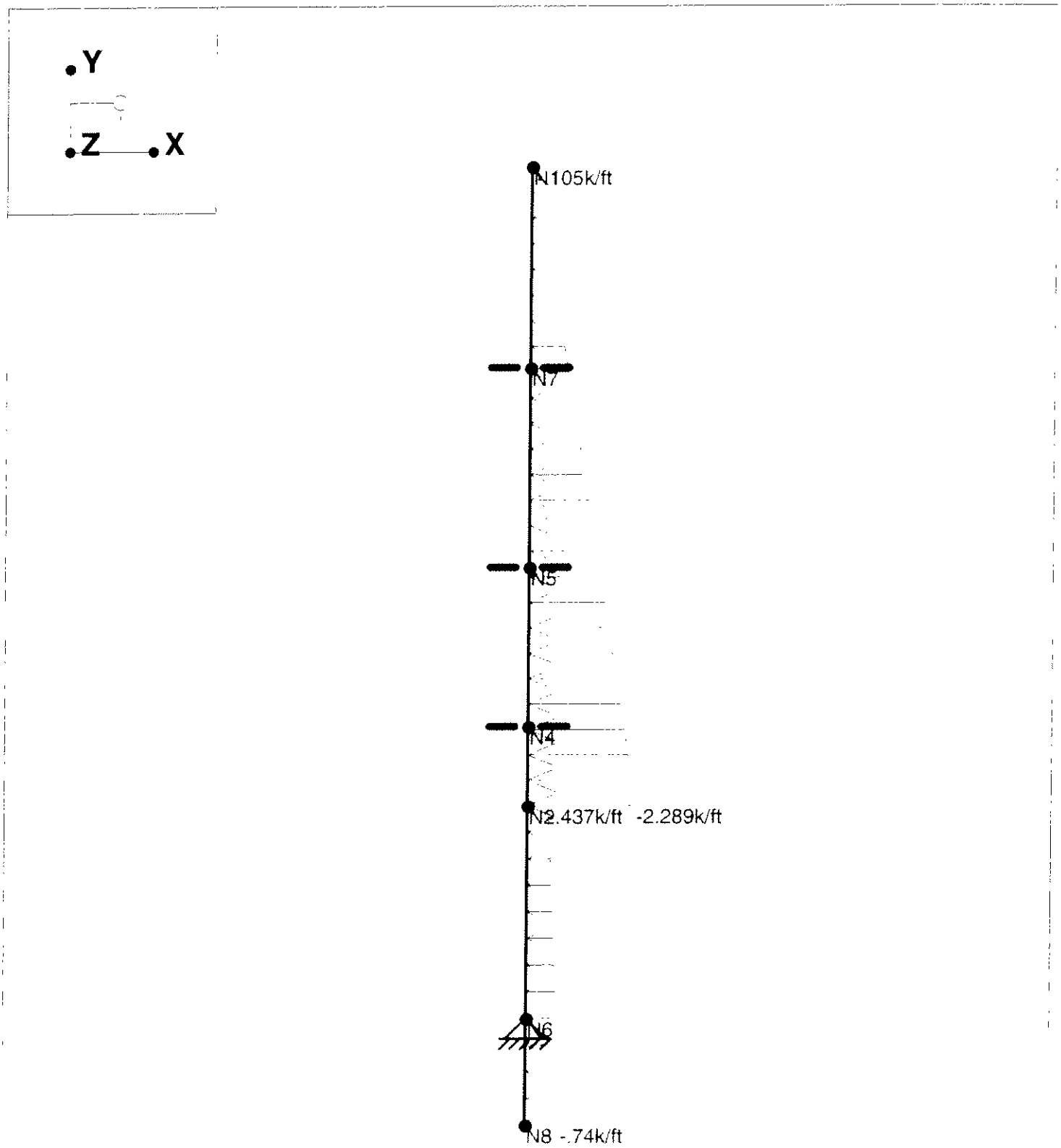
$\phi$ = Friction angle

| | | | | |
|---|---|---|---|---|
| **Check Sliding** | | | | |
| Reaction at Embedment = | 4146 lb | | | |
| Allowable Reaction = | 4622 lb | | | |
| Factor of Safety = | 1.7 | (Minimum FOS = 1.5) | | |
| **Check Overturning** | | | | |
| $P_{tieback(top)}$ = | 5,251 lb | OK | Factor of Safety = | 5.6 |
| $P_{tieback(middle)}$ = | 5,399 lb | OK | Factor of Safety = | 5.4 |
| $P_{tieback(bottom)}$ = | 9,064 lb | OK | Factor of Safety = | 3.2 |
| | | | (Minimum FOS = 1.5) | |
| **Determine Max Moment in Pile** | | | | |
| $M_{max}$ = | 4,200 ft-lb | | | |
| **Pile Design** | | | | |
| A = | 10.32 $in^2$ | | | |
| I = | 120.51 $in^4$ | | | |
| S = | 24.10 $in^3$ | | | |
| $f_b$ = | 23.76 ksi | | | |
| $M_{total}$ = | 4.20 ft-k | OK | | |
| $M_{allowable}$ = | 47.72 ft-k | | | |
| **Cable Design - 3/4" Diameter Cable** | | | | |
| Breaking Strength = | 58,800 lb | | | |
| Factor of Safety = | 3 | | | |
| Allowable Load = | 19,600 lb | | | |
| Allowable Load per wall = | 9,800 lb | | | |
| Allowable Load per bay = | 9,800 lb | | | |
| **Timber Design** | | | | |
| A = | 26.25 $in^2$ | | | |
| I = | 26.80 $in^4$ | | | |
| S = | 15.31 $in^3$ | | $f_v = \frac{3V_{max}}{2bd}$ | |
| $f_b$ = | 1407.60 psi | | | |
| $M_{total}$ = | 536.48 ft-lb | OK | $F'_{v(allowable)} = F_v C_R C_M C_F$ | |
| $M_{allowable}$ = | 1796.16 ft-lb | | Where, | |
| $f_v$ = | 40.88 psi | OK | | |
| $F'_{v(allowable)}$ = | 203.7 psi | | $F'_v$ = Adjusted allowable shear stress | |
| | | | $C_{R,M,F}$ = Wood Modification Factors | |
| **Whaler Design (for tieback)** | | | | |
| $F_b$ = | 23.76 ksi | | | |
| $S_{x(req)}$ = | 3.98 $in^3$ | 2C7x9.8 | $S_{x(req)} = \frac{M_{max}}{F_b}$ | |
| $S_x$ = | 12.14 $in^3$ | | | |
| $M_{total}$ = | 8.1 ft-lb | | | |
| $M_{allowable}$ = | 24.0 ft-lb | OK | | |




Results for LC 1, Design

| | | |
|---|---|---|
| Parkhill, Smith & Cooper | NRCS 16' Headwall | |
| Matt Laverty | | Nov 1, 2006 at 12:39 AM |
| 2926.04 | | 16 foot wall.r2d |




Loads: LC 1, Design
Results for LC 1, Design

| | | |
|---|---|---|
| Parkhill, Smith & Cooper | NRCS 16' Headwall | |
| Matt Laverty | | Nov 1, 2006 at 12:39 AM |
| 2926.04 | | 16 foot wall.r2d |

## Basic Load Cases

| | BLC Description | Category | X Gravity | Y Gravity | Joint | Point | Distributed |
|---|---|---|---|---|---|---|---|
| 1 | Surcharge (wall) | None | | | | | 1 |
| 2 | Surcharge (pile) | None | | | | | 1 |
| 3 | Soil (wall) | None | | | | | 1 |
| 4 | Soil (pile) | None | | | | | 1 |

## Joint Boundary Conditions

| | Joint Label | X [k/in] | Y [k/in] | Rotation[k-ft/rad] | Footing |
|---|---|---|---|---|---|
| 1 | N4 | Reaction | | | |
| 2 | N5 | Reaction | | | |
| 3 | N6 | Reaction | Reaction | | |
| 4 | N7 | Reaction | | | |

## Joint Coordinates and Temperatures

| | Label | X [ft] | Y [ft] | Temp [F] |
|---|---|---|---|---|
| 1 | N1 | 0 | 24 | 0 |
| 2 | N2 | 0 | 8 | 0 |
| 3 | N3 | 0 | 0 | 0 |
| 4 | N4 | 0 | 10 | 0 |
| 5 | N5 | 0 | 14 | 0 |
| 6 | N6 | 0 | 2.667 | 0 |
| 7 | N7 | 0 | 19 | 0 |
| 8 | N8 | 0 | 0 | 0 |

## Joint Reactions (By Combination)

| | LC | Joint Label | X [k] | Y [k] | MZ [k-ft] |
|---|---|---|---|---|---|
| 1 | 1 | N4 | 9.064 | 0 | 0 |
| 2 | 1 | N5 | 5.399 | 0 | 0 |
| 3 | 1 | N6 | 4.146 | 0 | 0 |
| 4 | 1 | N7 | 5.251 | 0 | 0 |
| 5 | 1 | Totals: | 23.86 | 0 | |
| 6 | 1 | COG (ft): | NC | NC | |

## Load Combinations

| | Description | Solve | PD... | SR... | BLC | Factor | BLC | Factor | BLC | Factor | BLC | Factor | BLC | Factor | BLC | Factor | BLC | Factor | BLC | Factor |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Design | Yes | | | 1 | 3 | 2 | 1 | 3 | 3 | 4 | 1 | | | | | | | | |

## Member Distributed Loads (BLC 1 : Surcharge (wall))

| | Member Label | Direction | Start Magnitude[k/ft,d... | End Magnitude[k/ft,d... | Start Location[ft,%] | End Location[ft,%] |
|---|---|---|---|---|---|---|
| 1 | M2 | X | -.035 | -.035 | 0 | 0 |

## Member Distributed Loads (BLC 2 : Surcharge (pile))

| | Member Label | Direction | Start Magnitude[k/ft,d... | End Magnitude[k/ft,d... | Start Location[ft,%] | End Location[ft,%] |
|---|---|---|---|---|---|---|
| 1 | M1 | X | -.03 | -.03 | 0 | 0 |

## Member Distributed Loads (BLC 3 : Soil (wall))

| | Member Label | Direction | Start Magnitude[k/ft,d... | End Magnitude[k/ft,d... | Start Location[ft,%] | End Location[ft,%] |
|---|---|---|---|---|---|---|
| 1 | M2 | X | -.728 | 0 | 0 | 0 |

## Member Distributed Loads (BLC 4 : Soil (pile))

| | Member Label | Direction | Start Magnitude[k/ft,d... | End Magnitude[k/ft,d... | Start Location[ft,%] | End Location[ft,%] |
|---|---|---|---|---|---|---|
| 1 | M1 | X | -.71 | -.407 | 0 | 0 |

## Member Section Forces

| | LC | Member Label | Sec | Axial[k] | Shear[k] | Moment[k-ft] |
|---|---|---|---|---|---|---|
| 1 | 1 | M1 | 1 | 0 | 0 | 0 |
| 2 | | | 2 | 0 | 1.404 | -1.43 |
| 3 | | | 3 | 0 | -1.489 | .01 |
| 4 | | | 4 | 0 | -.388 | 1.862 |
| 5 | | | 5 | 0 | .562 | 1.662 |
| 6 | 1 | M2 | 1 | 0 | .562 | 1.662 |
| 7 | | | 2 | 0 | -.438 | .685 |
| 8 | | | 3 | 0 | .043 | .746 |
| 9 | | | 4 | 0 | -1.512 | -2.296 |
| 10 | | | 5 | 0 | 0 | 0 |

# APPENDIX C

# DRAWINGS

# APPENDIX D

# ROCK RIPRAP OUTLET PROTECTION

# Appendix D

## Rock Riprap Outlet Protection

December 2006

PSC Project # 01292604

**Certification: All components comply with the design requirements set forth in the Statement of Work, Texas NRCS Conservation Practice Standard 578, Headwalls and other referenced codes.**

PSC **Parkhill, Smith & Cooper, Inc.**
Engineers ▪ Architects ▪ Planners

# Appendix D

## Rock Riprap Outlet Protection

December 2006

PSC Project # 01292604

STATE OF TEXAS
EDWIN EUGENE DAVIS
46223
LICENSED
PROFESSIONAL ENGINEER
12/21/06

**Certification: All components comply with the design requirements set forth in the Statement of Work, Texas NRCS Conservation Practice Standard 578, Headwalls and other referenced codes.**

PSC **Parkhill, Smith & Cooper, Inc.**
Engineers ▪ Architects ▪ Planners

I certify to the best of my knowledge that Texas Standard drawings:

| | |
|---|---|
| **TX-EN-0500** | **Headwalls with Timbers and Steel Pipe Piles**<br>**6 foot maximum height**<br>**Sheets 4 of 5 and 5 of 5** |
| **TX-EN-0501** | **Headwalls with Timbers and Steel Pipe Piles**<br>**11 foot maximum height**<br>**Sheets 4 of 5 and 5 of 5** |
| **TX-EN-0502** | **Headwalls with Timbers and Steel Pipe Piles**<br>**16 foot maximum height**<br>**Sheets 4 of 5 and 5 of 5** |

meet the design requirements in the Statement of Work for Standard Drawing for Headwalls, USDA-NRCS Task Order 43-7442-4-1080, and Texas NRCS Conservation Practice Standard and Specifications, 578, Headwalls and other referenced codes.

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**APPENDIX A – CALCULATIONS**

# PURPOSE

This engineering report documents the design procedure for optional rock riprap headwall used downstream of steel pipe pile headwalls. Channel instability can develop downstream from culvert outlets due to localized erosion known as a scour hole. Scour hole or localized erosion can occur even if the downstream channel is stable. The severity of damage to be anticipated depends upon the conditions existing or created at the outlet. In many situations, flow conditions can produce scour resulting in embankment erosion as well as structural damage to the headwall or culvert. A flat rock riprap apron can be used to prevent erosion at the transition from a pipe or box culvert to a natural channel.

# OVERVIEW

The downstream optional rock riprap is briefly described as follows:

Placed rock riprap at the end of the outlet having sufficient average size of stone and configuration of a horizontal blanket to control or prevent localized scour downstream of an outlet. Protection is provided primarily by having sufficient length and flare to dissipate energy by expanding the flow. Riprap aprons are appropriate when the culvert outlet Froud Number is less than or equal to 2.5.

Froude number - A unit less mathematical expression used to describe a flow field. Froude numbers greater than or equal to 1 are supercritical, less than 1 are subcritical. The equation for Froude number is

$$F = \frac{V^2}{gh}$$

where

F = the Froude number

V = the fluid velocity

g = gravity

h = fluid depth

## SOIL PROPERTIES

Parkhill, Smith & Cooper, Inc. (PSC) assumed outlet conditions of non-cohesive sandy soils, 145 pounds per cubic foot (pcf) for the unit weight of soil.

## TAILWATER CONDITIONS, DISCHARGE, CULVERT DIMENSIONS AND CASES

### General

PSC researched available literature for design criteria and design methods for rock riprap. Two publications provided good technical information and procedures which PSC incorporated to prepare this engineering report and the standard drawing. The Georgia Stormwater Management Manual, Section 4.5, Energy Dissipation Design included good design guidelines and procedures and even referenced 1975 USDA SCS nomographs for stone riprap sizing and apron length. PSC could not locate the original SCS source. However, PSC incorporated the procedures and conditions documented in the Georgia Stormwater Management Manual. The second publication, TM 5-820-3, AFM 88-5, Chap. 3, Drainage and Erosion-Control for Structures for Airfields and Heliports, June 1991, also contains similar design criteria and procedures with the added benefit of design formulas. Both references are reproduced in this design report in the appendix.

### Tailwater Conditions

Both references used by PSC included two conditions for downstream culvert tailwater levels, one for minimum and one for maximum tailwater conditions. Generally, if the tailwater is less than one half the discharge flow depth (pipe diameter if flowing full), minimum tailwater conditions exist. Otherwise, maximum tailwater conditions exist.

### Discharge and Culvert Dimensions

PSC examined full pipe discharges resulting from various culvert diameters on varying slopes.

**Culvert Diameters:** 12”, 18”, 24”, 30”, 36”, 42”, 48”, 54” and 60”
**Culvert Slopes:** 0.010 feet/foot to 0.10 feet per foot in 0.01 feet/foot increments
**Manning’s Coefficient:** 0.024 representing corrugated metal pipe

PSC used Haestad Methods, Inc., software, “FlowMaster” to calculate the discharge of these culverts sizes and slopes. The software printouts are include the appendix. A summary of the results is as follows:

| Rating Table for Circular Channel – Full Pipe Flow | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Discharge (cfs) | | | | | | | | |
| Channel Slope (ft/ft) | 12” | 18” | 24” | 30” | 36” | 42” | 48” | 54” | 60” |
| **0.01** | 1.93 | 5.69 | 12.2 | 22.2 | 36.1 | 54.5 | 77.8 | 107 | 141 |
| **0.02** | 2.73 | 8.05 | 17.3 | 31.4 | 51.1 | 77.1 | 110 | 151 | 200 |
| **0.03** | 3.34 | 9.85 | 21.2 | 38.5 | 62.6 | 94.4 | 135 | 185 | 244 |
| **0.04** | 3.86 | 11.4 | 24.5 | 44.4 | 72.2 | 109 | 156 | 213 | 282 |

| Rating Table for Circular Channel – Full Pipe Flow | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Discharge (cfs) | | | | | | | | |
| Channel Slope (ft/ft) | 12” | 18” | 24” | 30” | 36” | 42” | 48” | 54” | 60” |
| **0.05** | 4.32 | 12.7 | 27.4 | 49.7 | 80.8 | 122 | 174 | 238 | 315 |
| **0.06** | 4.73 | 13.9 | 30.0 | 54.4 | 88.5 | 133 | 191 | 261 | 346 |
| **0.07** | 5.11 | 15.0 | 32.4 | 58.8 | 95.6 | 144 | 206 | 282 | 373 |
| **0.08** | 5.46 | 16.1 | 34.7 | 62.8 | 102 | 154 | 220 | 301 | 399 |
| **0.09** | 5.79 | 17.1 | 36.8 | 66.6 | 108 | 163 | 233 | 320 | 423 |
| **0.10** | 6.10 | 18.0 | 38.8 | 70.2 | 114 | 172 | 246 | 337 | 446 |

## DESIGN PROCEDURES

The average size of stone ($d_{50}$) and configuration of a horizontal blanket of stone riprap at the outlet invert elevation required to control or prevent localized scour downstream can be estimated using formulas developed by TM 5-820-3. PSC considered two tailwater conditions, ½ full flow depth and full flow depth, which represents minimum tailwater conditions and maximum tailwater conditions.

### Minimum Average Size of Stone ($d_{50}$)

For a given discharge, culvert dimensions, and tailwater depth relative to the outlet invert, the minimum average size of stone ($d_{50}$) for a horizontal blanket of protection can be determined using the following formula:

$$d_{50} = \frac{D_o^2 C}{TW}\left(\frac{Q}{D_o^{5/2}}\right)^{4/3}$$

where

$d_{50}$ = diameter of average size stone (feet)

$D_o$ = diameter of circular culverts (feet)

C = coefficient = 0.020 for horizontal blanket

TW = tailwater depth above invert of culvert outlet (feet)

Q = discharge (cubic feet per second, cfs)

The maximum stone diameter ($D_{max}$) should be 1.5 times $d_{50}$ in a well graded riprap apron. The riprap thickness should be 1.5 times the maximum stone diameter or 6 inches, whichever is greater. Apron thickness can be reduced to 1.5 times $d_{50}$ when an appropriate filter fabric is used under the apron. PSC recommends using the filter fabric.

## Length of Stone Protection ($L_{sp}$)

The length of stone protection can be determined by the following formulas;

For TW less than ½ $D_o$ (Minimum Tailwater Condition)

$$L_{sp} = 1.8D_o\left(\frac{Q}{D_o^{5/2}}\right) + 7$$

where

$L_{sp}$ = length of stone protection (feet)

$D_o$ = diameter of circular culverts (feet)

Q = culvert discharge (cubic feet per second, cfs)

For TW equal to or greater than $D_o$ (Maximum Tailwater Condition)

$$L_{sp} = 3D_o\left(\frac{Q}{D_o^{5/2}}\right)$$

where

$L_{sp}$ = length of stone protection (feet)

$D_o$ = diameter of circular culverts (feet)

Q = culvert discharge (cubic feet per second, cfs)

As a check, PSC calculated the Froude number for each culvert discharge. When the Froude number exceeded 2.5, the tabular values were shaded grey. These values are not recommended.

### Horizontal Blanket Configuration

The recommended configuration of the horizontal blanket is shown in the following figure. The width of the stone protection ($W_{sp}$) is a function of the culvert diameter and $L_{sp}$ as follows:

For TW less than ½ $D_o$ Minimum Tailwater Condition)

$$W_{sp} = 3D_o + L_{sp}$$

where

$W_{sp}$ = width of stone protection

$D_o$ = diameter of circular culverts (feet)

$L_{sp}$ = length of stone protection (feet)

For TW equal to or greater than $D_o$ (Maximum Tailwater Condition)

$$W_{sp} = 3D_o + \frac{2L_{sp}}{5}$$

where

$W_{sp}$ = witdth of stone protection

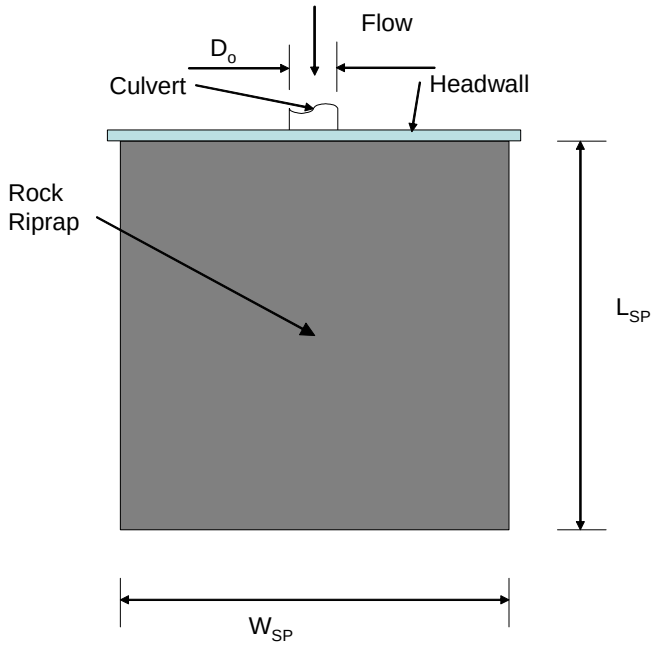
$D_o$ = diameter of circular culverts (feet)

$L_{sp}$ = length of stone protection (feet)

## DESIGN SUMMARY

Based on the above design procedures PSC prepared tables for each of the nine culvert diameters (Do), the ten different flows (Q) and the two tailwater conditions, for a total of 18 tables. These tables are included in this engineering report in Appendix A. While these tables can be used to select the rock riprap dimensions and quantities, the intent of a standard drawing is to simplify and standardize the dimensions. PSC reviewed the tabular data to determine an appropriate method to simplify and standardize the rock riprap apron dimensions and properties. Minimum tailwater conditions generally require the larger rock size ($d_{50}$) and wider aprons ($W_{sp}$). Maximum tailwater conditions generally require longer apron lengths ($L_{sp}$). PSC also noted there were fewer changes in dimensions at the lower flow regimes. Considering that a Froude number less than 1 indicates subcritical flow, and that riprap aprons are appropriate when culvert outlet Froude Number is less than 2.5, PSC prepared a comparison table for the varying culvert dimensions based on a Froude Number of 1 and 2.5. PSC followed the same procedures and

used the same formulas to develop two tables, one for minimum tailwater conditions and one for maximum tailwater conditions. Using the results of these two tables, PSC selected the larger value from the two tables for rock size ($d_{50}$), apron length ($L_{sp}$) and apron width ($W_{sp}$). These values then become the basis for the standard drawing and bill of materials.




## BILL OF MATERIALS

### Stone Riprap Dimensions and Quantities

Using the standardized dimensions, PSC developed spreadsheets to document the $d_{50}$ (minimum average diameter of stone), $L_{sp}$ (length of stone protection) and width ($W_{sp}$). $d_{50}$ is rounded up to the nearest inch. $L_{sp}$ and $W_{sp}$ are rounded to the nearest foot. Based on these dimensions, the spreadsheet calculates the stone riprap volumes in cubic yards and tons based on a stone density of 165 pounds per cubic foot. The spreadsheet also includes the filter fabric quantities.

## REFERENCES

1. TM 5-820-3, AFM 88-5, CHAP. 3, Technical Manual, Drainage and Erosion-Control Structures for Airfield and Heliports, Departments of the Army, and the Air Force, June 1991

2. Georgia Stormwater Management (Volume 2 (Technical Handbook), Section 4.5, Energy Dissipation Design.

SECTION

4.5

# ENERGY DISSIPATION DESIGN

## 4.5.1 Overview

### 4.5.1.1 Introduction

The outlets of pipes and lined channels are points of critical erosion potential. Stormwater that is transported through man-made conveyance systems at design capacity generally reaches a velocity that exceeds the capacity of the receiving channel or area to resist erosion. To prevent scour at stormwater outlets, protect the outlet structure and minimize the potential for downstream erosion, a flow transition structure is needed to absorb the initial impact of flow and reduce the speed of the flow to a non-erosive velocity.

*Energy dissipators* are engineered devices such as rip-rap aprons or concrete baffles placed at the outlet of stormwater conveyances for the purpose of reducing the velocity, energy and turbulence of the discharged flow.

### 4.5.1.2 General Criteria

- Erosion problems at culvert, pipe and engineered channel outlets are common. Determination of the flow conditions, scour potential, and channel erosion resistance shall be standard procedure for all designs.
- Energy dissipators shall be employed whenever the velocity of flows leaving a stormwater management facility exceeds the erosion velocity of the downstream area channel system.
- Energy dissipator designs will vary based on discharge specifics and tailwater conditions.
- Outlet structures should provide uniform redistribution or spreading of the flow without excessive separation and turbulence.

### 4.5.1.3 Recommended Energy Dissipators

For many designs, the following outlet protection devices and energy dissipators provide sufficient protection at a reasonable cost:

- Riprap apron
- Riprap outlet basins
- Baffled outlets

This section focuses on the design on these measures. The reader is referred to the Federal Highway Administration Hydraulic Engineering Circular No. 14 entitled, Hydraulic Design of Energy Dissipators for Culverts and Channels, for the design procedures of other energy dissipators.

## 4.5.2 Symbols and Definitions

To provide consistency within this section as well as throughout this Manual, the symbols listed in Table 4.5-1 will be used. These symbols were selected because of their wide use. In some cases, the same symbol is used in existing publications for more than one definition. Where this occurs in this section, the symbol will be defined where it occurs in the text or equations.

**Table 4.5-1** Symbols and Definitions

| Symbol | Definition | Units |
|---|---|---|
| $A$ | Cross-sectional area | $ft^2$ |
| $D$ | Height of box culvert | ft |
| $d_{50}$ | Size of riprap | ft |
| $d_w$ | Culvert width | ft |
| $Fr$ | Froude Number | - |
| $g$ | Acceleration of gravity | $ft/s^2$ |
| $h_s$ | Depth of dissipator pool | ft |
| $L$ | Length | ft |
| $L_a$ | Riprap apron length | ft |
| $L_B$ | Overall length of basin | ft |
| $L_s$ | Length of dissipator pool | ft |
| $PI$ | Plasticity index | - |
| $Q$ | Rate of discharge | cfs |
| $S_v$ | Saturated shear strength | $lbs/in^2$ |
| $t$ | Time of scour | min. |
| $t_c$ | Critical tractive shear stress | $lbs/in^2$ |
| $TW$ | Tailwater depth | ft |
| $V_L$ | Velocity L feet from brink | ft/s |
| $V_o$ | Normal velocity at brink | ft/s |
| $V_o$ | Outlet mean velocity | ft/s |
| $V_s$ | Volume of dissipator pool | $ft^2$ |
| $W_o$ | Diameter or width of culvert | ft |
| $W_s$ | Width of dissipator pool | ft |
| $y_e$ | Hydraulic depth at brink | ft |
| $y_o$ | Normal flow depth at brink | ft |

## 4.5.3 Design Guidelines

(1) If outlet protection is required, choose an appropriate type. Suggested outlet protection facilities and applicable flow conditions (based on Froude number and dissipation velocity) are described below:

a. Riprap aprons may be used when the outlet Froude number (Fr) is less than or equal to 2.5. In general, riprap aprons prove economical for transitions from culverts to overland sheet flow at terminal outlets, but may also be used for transitions from culvert sections to stable channel sections. Stability of the surface at the termination of the apron should be considered.

b. Riprap outlet basins may also be used when the outlet Fr is less than or equal to 2.5. They are generally used for transitions from culverts to stable channels. Since riprap outlet basins function by creating a hydraulic jump to dissipate energy, performance is impacted by tailwater conditions.

c. Baffled outlets have been used with outlet velocities up to 50 feet per second. Practical application typically requires an outlet Fr between 1 and 9. Baffled outlets may be used at both terminal outlet and channel outlet transitions. They function by dissipating energy through impact and turbulence and are not significantly affected by tailwater conditions.

(2) When outlet protection facilities are selected, appropriate design flow conditions and site-specific factors affecting erosion and scour potential, construction cost, and long-term durability should be considered.

(3) If outlet protection is not provided, energy dissipation will occur through formation of a local scourhole. A cutoff wall will be needed at the discharge outlet to prevent structural undermining. The wall depth should be slightly greater than the computed scourhole depth, $h_S$. The scourhole should then be stabilized. If the scourhole is of such size that it will present maintenance, safety, or aesthetic problems, other outlet protection will be needed.

(4) Evaluate the downstream channel stability and provide appropriate erosion protection if channel degradation is expected to occur. Figure 4.5-1 provides the riprap size recommended for use downstream of energy dissipators.

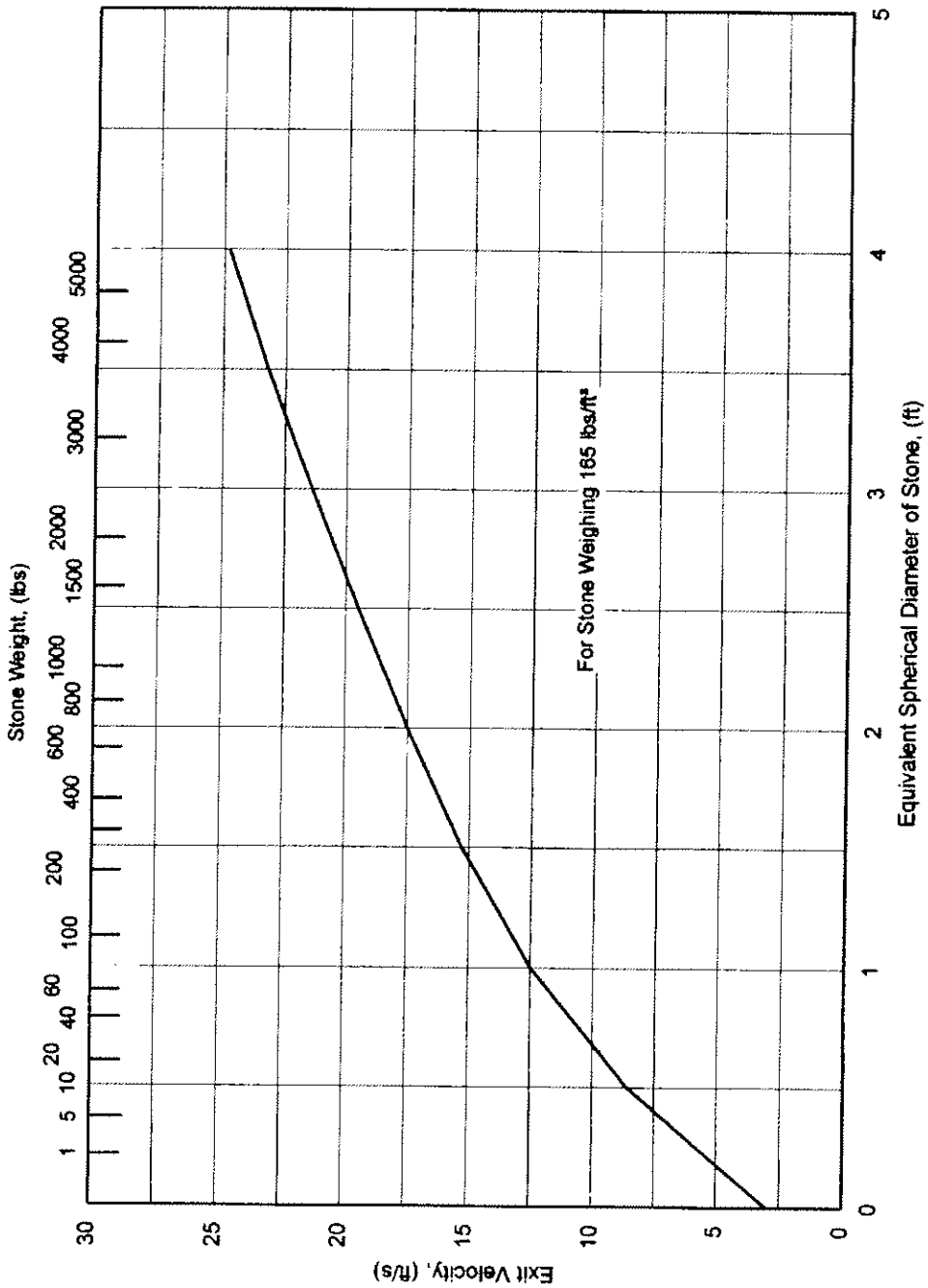



**Figure 4.5-1 Riprap Size for Use Downstream of Energy Dissipator**
(Source: Searcy, 1967)

## 4.5.4 Riprap Aprons

### 4.5.4.1 Description

A riprap-lined apron is a commonly used practice for energy dissipation because of its relatively low cost and ease of installation. A flat riprap apron can be used to prevent erosion at the transition from a pipe or box culvert outlet to a natural channel. Protection is provided primarily by having sufficient length and flare to dissipate energy by expanding the flow. Riprap aprons are appropriate when the culvert outlet Fr is less than or equal to 2.5.

### 4.5.4.2 Design Procedure

The procedure presented in this section is taken from USDA, SCS (1975). Two sets of curves, one for minimum and one for maximum tailwater conditions, are used to determine the apron size and the median riprap diameter, $d_{50}$. If tailwater conditions are unknown, or if both minimum and maximum conditions may occur, the apron should be designed to meet criteria for both. Although the design curves are based on round pipes flowing full, they can be used for partially full pipes and box culverts. The design procedure consists of the following steps:

(Step 1) If possible, determine tailwater conditions for the channel. If tailwater is less than one-half the discharge flow depth (pipe diameter if flowing full), minimum tailwater conditions exist and the curves in Figure 4.5-2 apply. Otherwise, maximum tailwater conditions exist and the curves in Figure 4.5-3 should be used.

(Step 2) Determine the correct apron length and median riprap diameter, $d_{50}$, using the appropriate curves from Figures 4.5-2 and 4.5-3. If tailwater conditions are uncertain, find the values for both minimum and maximum conditions and size the apron as shown in Figure 4.5-4.

a. *For pipes flowing full:*

Use the depth of flow, d, which equals the pipe diameter, in feet, and design discharge, in cfs, to obtain the apron length, $L_a$, and median riprap diameter, $d_{50}$, from the appropriate curves.

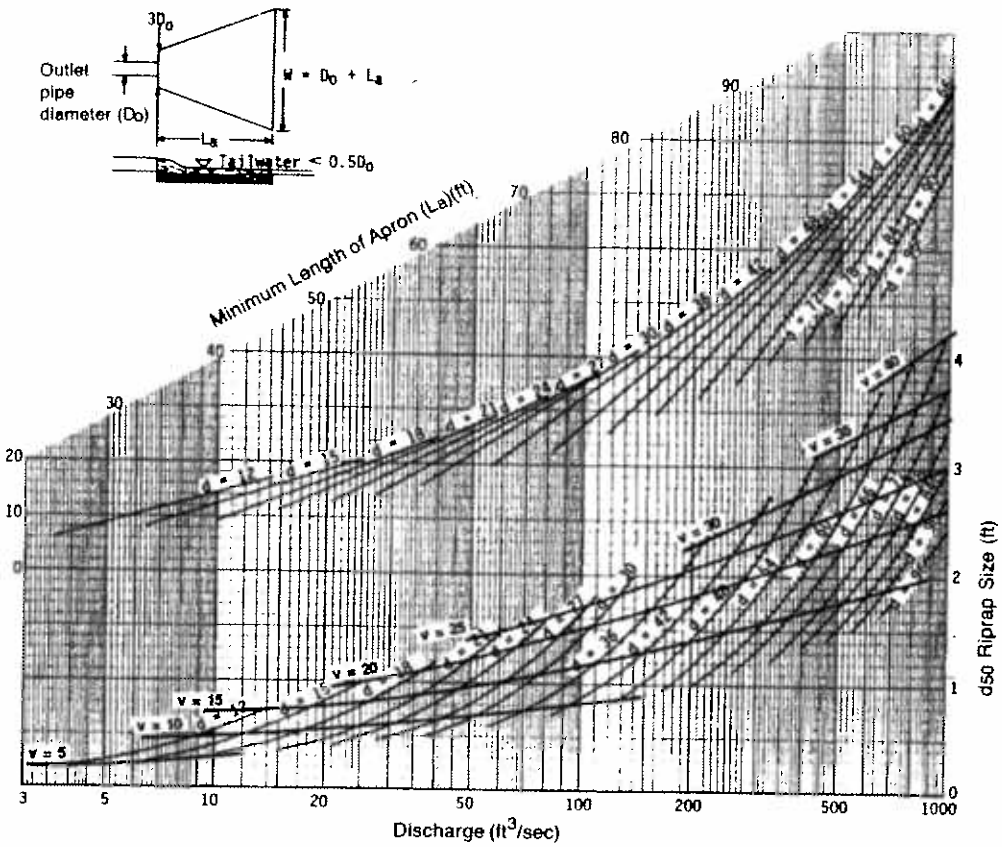
b. *For pipes flowing partially full:*

Use the depth of flow, d, in feet, and velocity, v, in ft/s. On the lower portion of the appropriate figure, find the intersection of the d and v curves, then find the riprap median diameter, $d_{50}$, from the scale on the right. From the lower d and v intersection point, move vertically to the upper curves until intersecting the curve for the correct flow depth, d. Find the minimum apron length, $L_a$, from the scale on the left.

c. *For box culverts:*

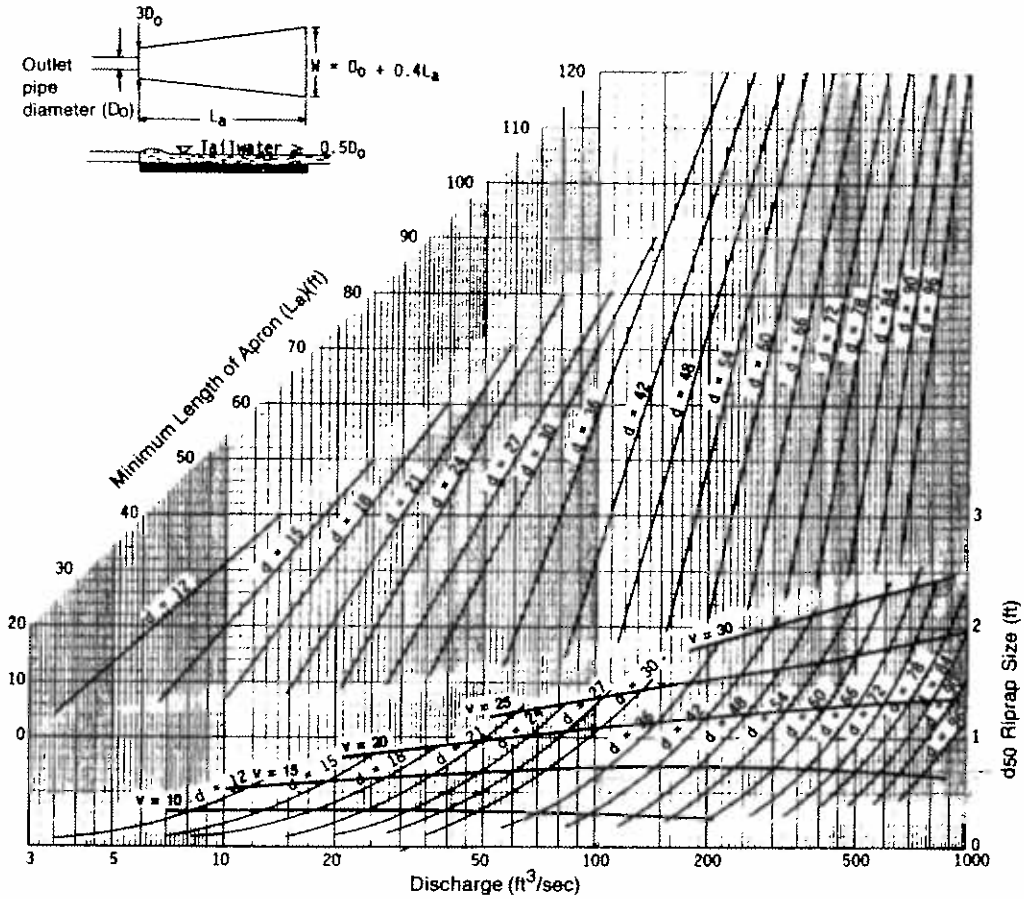
Use the depth of flow, d, in feet, and velocity, v, in feet/second. On the lower portion of the appropriate figure, find the intersection of the d and v curves, then find the riprap median diameter, $d_{50}$, from the scale on the right. From the lower d and v intersection point, move vertically to the upper curve until intersecting the curve equal to the flow depth, d. Find the minimum apron length, $L_a$, using the scale on the left.

(Step 3) If tailwater conditions are uncertain, the median riprap diameter should be the larger of the values for minimum and maximum conditions. The dimensions of the apron will be as shown in Figure 4.5-4. This will provide protection under either of the tailwater conditions.



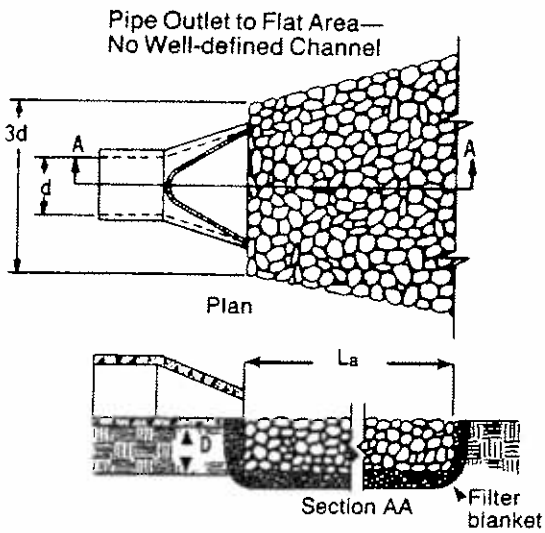

Curves may not be extrapolated.

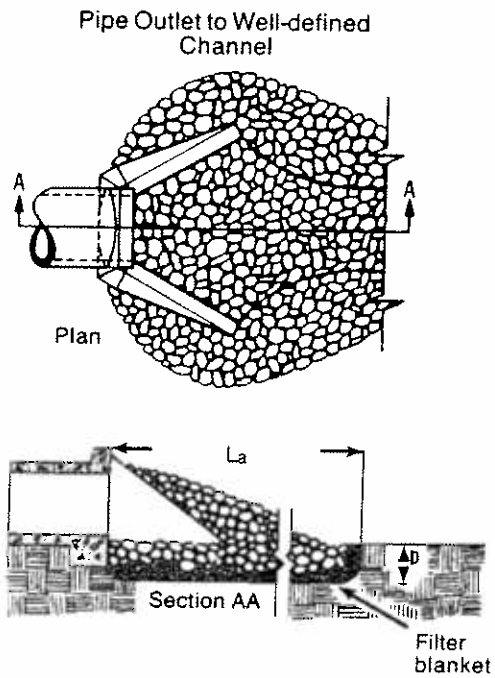
**Figure 4.5-2 Design of Riprap Apron under Minimum Tailwater Conditions**
(Source: USDA, SCS, 1975)




Curves may not be extrapolated.

**Figure 4.5-3 Design of Riprap Apron under Maximum Tailwater Conditions**
(Source: USDA, SCS, 1975)




**Notes**

1. $L_a$ is the length of the riprap apron.
2. D = 1.5 times the maximum stone diameter but not less than 6".
3. In a well-defined channel extend the apron up the channel banks to an elevation of 6" above the maximum tailwater depth or to the top of the bank, whichever is less.
4. A filter blanket or filter fabric should be installed between the riprap and soil foundation.

**Figure 4.5-4 Riprap Apron**
(Source: Manual for Erosion and Sediment Control in Georgia, 1996)

### 4.5.4.3 Design Considerations

The following items should be considered during riprap apron design:

- The maximum stone diameter should be 1.5 times the median riprap diameter. $d_{max} = 1.5 \times d_{50}$ , $d_{50}$ = the median stone size in a well-graded riprap apron.

- The riprap thickness should be 1.5 times the maximum stone diameter or 6 inches, whichever is greater. Apron thickness = $1.5 \times d_{max}$
  (Apron thickness may be reduced to $1.5 \times d_{50}$ when an appropriate filter fabric is used under the apron.)

- The apron width at the discharge outlet should be at least equal to the pipe diameter or culvert width, $d_w$. Riprap should extend up both sides of the apron and around the end of the pipe or culvert at the discharge outlet at a maximum slope of 2:1 and a height not less than the pipe diameter or culvert height, and should taper to the flat surface at the end of the apron.

- If there is a well-defined channel, the apron length should be extended as necessary so that the downstream apron width is equal to the channel width. The sidewalls of the channel should not be steeper than 2:1.

- If the ground slope downstream of the apron is steep, channel erosion may occur. The apron should be extended as necessary until the slope is gentle enough to prevent further erosion.

- The potential for vandalism should be considered if the rock is easy to carry. If vandalism is a possibility, the rock size must be increased or the rocks held in place using concrete or grout.

### 4.5.4.4 Example Designs

Example 1 Riprap Apron Design for Minimum Tailwater Conditions

A flow of 280 cfs discharges from a 66-in pipe with a tailwater of 2 ft above the pipe invert. Find the required design dimensions for a riprap apron.

(1) Minimum tailwater conditions = $0.5\ d_o$, $d_o$ = 66 in = 5.5 ft; therefore, $0.5\ d_o$ = 2.75 ft.

(2) Since TW = 2 ft, use Figure 4.5-2 for minimum tailwater conditions.

(3) By Figure 4.5-2, the apron length, $L_a$, and median stone size, $d_{50}$, are 38 ft and 1.2 ft, respectively.

(4) The downstream apron width equals the apron length plus the pipe diameter:
$W = d + L_a = 5.5 + 38 = 43.5$ ft

(5) Maximum riprap diameter is 1.5 times the median stone size:
$1.5\ (d_{50}) = 1.5\ (1.2) = 1.8$ ft

(6) Riprap depth = $1.5\ (d_{max}) = 1.5\ (1.8) = 2.7$ ft.

Example 2 Riprap Apron Design for Maximum Tailwater Conditions

A concrete box culvert 5.5 ft high and 10 ft wide conveys a flow of 600 cfs at a depth of 5.0 ft. Tailwater depth is 5.0 ft above the culvert outlet invert. Find the design dimensions for a riprap apron.

(1) Compute $0.5\ d_o = 0.5\ (5.0) = 2.5$ ft.

(2) Since TW = 5.0 ft is greater than 2.5 ft, use Figure 4.5-3 for maximum tailwater conditions. $v = Q/A = [600/(5)\ (10)] = 12$ ft/s

(3) On Figure 4.5-3, at the intersection of the curve, $d_o = 60$ in and $v = 12$ ft/s, $d_{50} = 0.4$ ft. Reading up to the intersection with d = 60 in, find $L_a = 40$ ft.

(4) Apron width downstream = $d_w + 0.4\ L_a = 10 + 0.4\ (40) = 26$ ft.

(5) Maximum stone diameter = $1.5\ d_{50} = 1.5\ (0.4) = 0.6$ ft.

(6) Riprap depth = $1.5\ d_{max} = 1.5\ (0.6) = 0.9$ ft.

## 4.5.5 Riprap Basins

### 4.5.5.1 Description

Another method to reduce the exit velocities from stormwater outlets is through the use of a riprap basin. A riprap outlet basin is a preshaped scourhole lined with riprap that functions as an energy dissipator by forming a hydraulic jump.

### 4.5.5.2 Basin Features

General details of the basin recommended in this section are shown in Figure 4.5-5. Principal features of the basin are:

- The basin is preshaped and lined with riprap of median size ($d_{50}$).
- The floor of the riprap basin is constructed at an elevation of $h_s$ below the culvert invert. The dimension $h_s$ is the approximate depth of scour that would occur in a thick pad of riprap of size $d_{50}$ if subjected to design discharge. The ratio of $h_s$ to $d_{50}$ of the material should be between 2 and 4.
- The length of the energy dissipating pool is $10 \times h_s$ or $3 \times W_o$, whichever is larger. The overall length of the basin is $15 \times h_s$ or $4 \times W_o$, whichever is larger.

### 4.5.5.3 Design Procedure

The following procedure should be used for the design of riprap basins.

(Step 1) Estimate the flow properties at the brink (outlet) of the culvert. Establish the outlet invert elevation such that $TW/y_o \leq 0.75$ for the design discharge.

(Step 2) For subcritical flow conditions (culvert set on mild or horizontal slope) use Figure 4.5-6 or Figure 4.5-7 to obtain $y_o/D$, then obtain $V_o$ by dividing Q by the wetted area associated with $y_o$. D is the height of a box culvert. If the culvert is on a steep slope, $V_o$ will be the normal velocity obtained by using the Manning equation for appropriate slope, section, and discharge.

(Step 3) For channel protection, compute the Froude number for brink conditions with $y_e = (A/2)^{1.5}$. Select $d_{50}/y_e$ appropriate for locally available riprap (usually the most satisfactory results will be obtained if $0.25 < d_{50}/y_e < 0.45$). Obtain $h_s/y_e$ from Figure 4.5-8, and check to see that $2 < h_s/d_{50} < 4$. Recycle computations if $h_s/d_{50}$ falls out of this range.

(Step 4) Size basin as shown in Figure 4.5-5.

(Step 5) Where allowable dissipator exit velocity is specified:

a. Determine the average normal flow depth in the natural channel for the design discharge.

b. Extend the length of the energy basin (if necessary) so that the width of the energy basin at section A-A, Figure 4.5-5, times the average normal flow depth in the natural channel is approximately equal to the design discharge divided by the specified exit velocity.

(Step 6) In the exit region of the basin, the walls and apron of the basin should be warped (or transitioned) so that the cross section of the basin at the exit conforms to the cross section of the natural channel. Abrupt transition of surfaces should be avoided to minimize separation zones and resultant eddies.

(Step 7) If high tailwater is a possibility and erosion protection is necessary for the downstream channel, the following design procedure is suggested:

- Design a conventional basin for low tailwater conditions in accordance with the instructions above.
- Estimate centerline velocity at a series of downstream cross sections using the information shown in Figure 4.5-9.
- Shape downstream channel and size riprap using Figure 4.5-1 and the stream velocities obtained above.

Material, construction techniques, and design details for riprap should be in accordance with specifications in the Federal Highway publication HEC No. 11 entitled Use of Riprap For Bank Protection.

# CHAPTER 5

# STORM DRAINS AND CULVERTS

## 5-1. General.

The storm-drain system should have sufficient capacity to convey runoff from the design storm within the barrel of the conduit. Hydraulic design of the storm-drain system is discussed in TM 5-820-4/AFM 88-5 chapter 4. A drainage culvert is a relatively short conduit used to convey flow through a roadway embankment or past some other type of flow obstruction. Culverts are constructed from a variety of materials and are available in many different shapes and configurations. Culvert hydraulics and diagrams, charts, coefficients, and related information useful in design of culverts are shown in TM 5-820-4/AFM 88-5 chapter 4.

## 5-2. Headwalls and endwalls.

*a.* The normal functions of a headwall or wingwall are to recess the inflow or outflow end of the culvert barrel into the, fill slope to improve entrance flow conditions, to anchor the pipe and to prevent disjointing caused by excessive pressures, to control erosion and scour resulting from excessive velocities and turbulences, and to prevent adjacent soil from sloughing into the waterway opening.

*b.* Headwalls are particularly desirable as a cutoff to prevent saturation sloughing, piping, and erosion of the embankment. Provisions for drainage should be made over the center of the head-wall to prevent scouring along the sides of the walls.

*c.* Whether or not a headwall is desirable depends on the expected flow conditions and embankment stability. Erosion protection such as riprap or sacked concrete with a sand-cement ratio of 9:1 may be required around the culvert entrance if a headwall is not used.

*d.* In the design of headwalls some degree of entrance improvement should always be considered. The most efficient entrances would incorporate one or more of such geometric features as elliptical arcs, circular arcs, tapers, and parabolic drop-down curves. Elaborate inlet design for a culvert would be justifiable only in unusual circumstances. The rounding or beveling of the entrance in almost any way will increase the culvert capacity for every design condition. These types of improvements provide a reduction in the loss of energy at the entrance for little or no additional cost.

*e.* Entrance structures (headwalls and wingwalls) protect the embankment from erosion and, if properly designed, may improve the hydraulic characteristics of the culvert. The height of these structures should be kept to the minimum that is consistent with hydraulic, geometric, and structural requirements. Several entrance structures are shown in figure 5-1. Straight headwalls (fig 5-la) are used for low to moderate approach velocity, light drift (small floating debris), broad or undefined approach channels, or small defined channels entering culverts with little change in alignment. The "L" headwall (fig 5-lb) is used if an abrupt change in flow direction is necessary with low to moderate velocities. Winged headwalls (fig 5-1c) are used for channels with moderate velocity and medium floating debris. Wingwalls are most effective when set flush with the edges of the culvert barrel, aligned with stream axis (fig 5-id) and placed at a flare angle of 18 to 45 degrees. Warped wingwalls (not shown) are used for well-defined channels with high-velocity flow and a free water surface. They are used primarily with box culverts. Warped headwalls are hydraulically efficient because they form a gradual transition from a trapezoidal channel to the barrel. The use of a drop-down apron in conjunction with these wingwalls may be particularly advantageous.

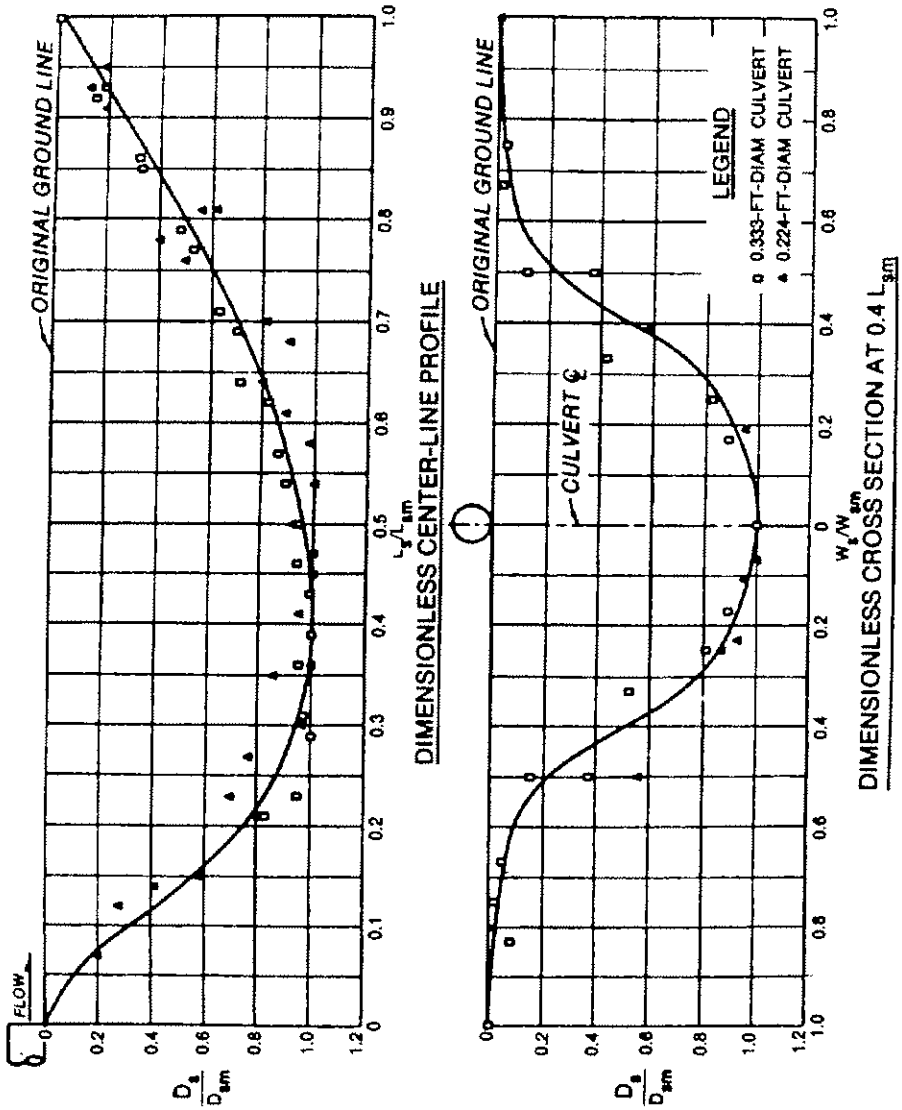



*Figure 5-9. Dimensionless scour hole geometry for maximum tailwater.*

## 5-4. Erosion control at outlet.

There are various methods of preventing scour and erosion at outlets and protecting the structure from undermining. Some of these methods will be discussed in subsequent paragraphs.

*a.* In some situations placement of riprap at the end of the outlet may be sufficient to protect the structure. The average size of stone ($d_{50}$) and configuration of a horizontal blanket of riprap at outlet invert elevation required to control or prevent localized scour downstream of an outlet can be estimated using the information in figures 5-10 to 5-12. For a given design discharge, culvert dimensions, and tailwater depth relative to the outlet invert, the minimum average size of stone ($d_{50}$) for a horizontal blanket of protection can be determined using data in figure 5-10. The length of stone protection (LSP) can be determined by the relations shown in figure 5-11. The variables are defined in appendix E, and the recommended configuration of the blanket is shown in figure 5-12.

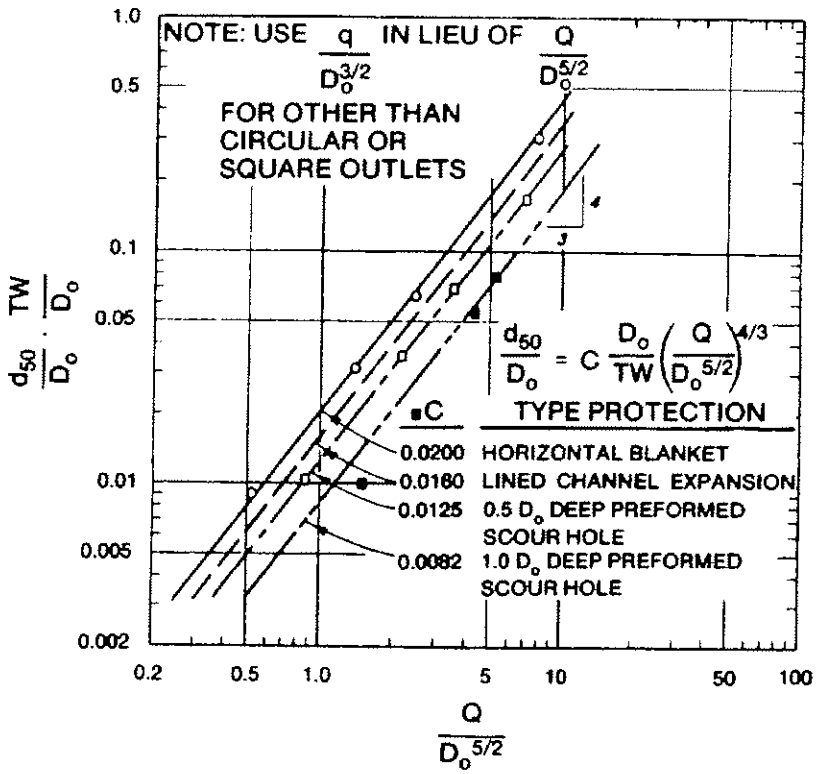



*Figure 5-10. Recommended size of protective stone.*

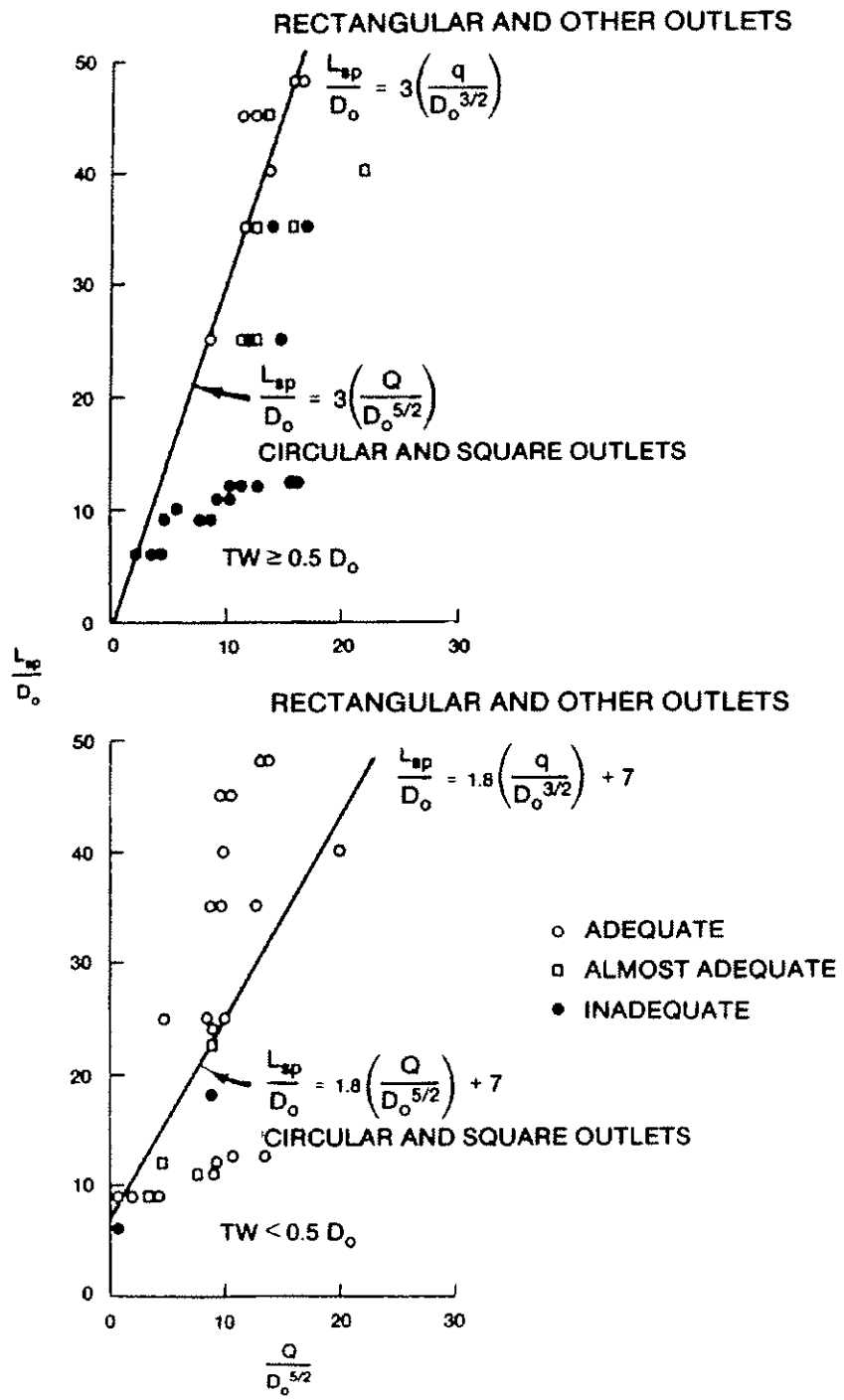



*Figure 5-11. Length of stone protection, horizontal blanket.*

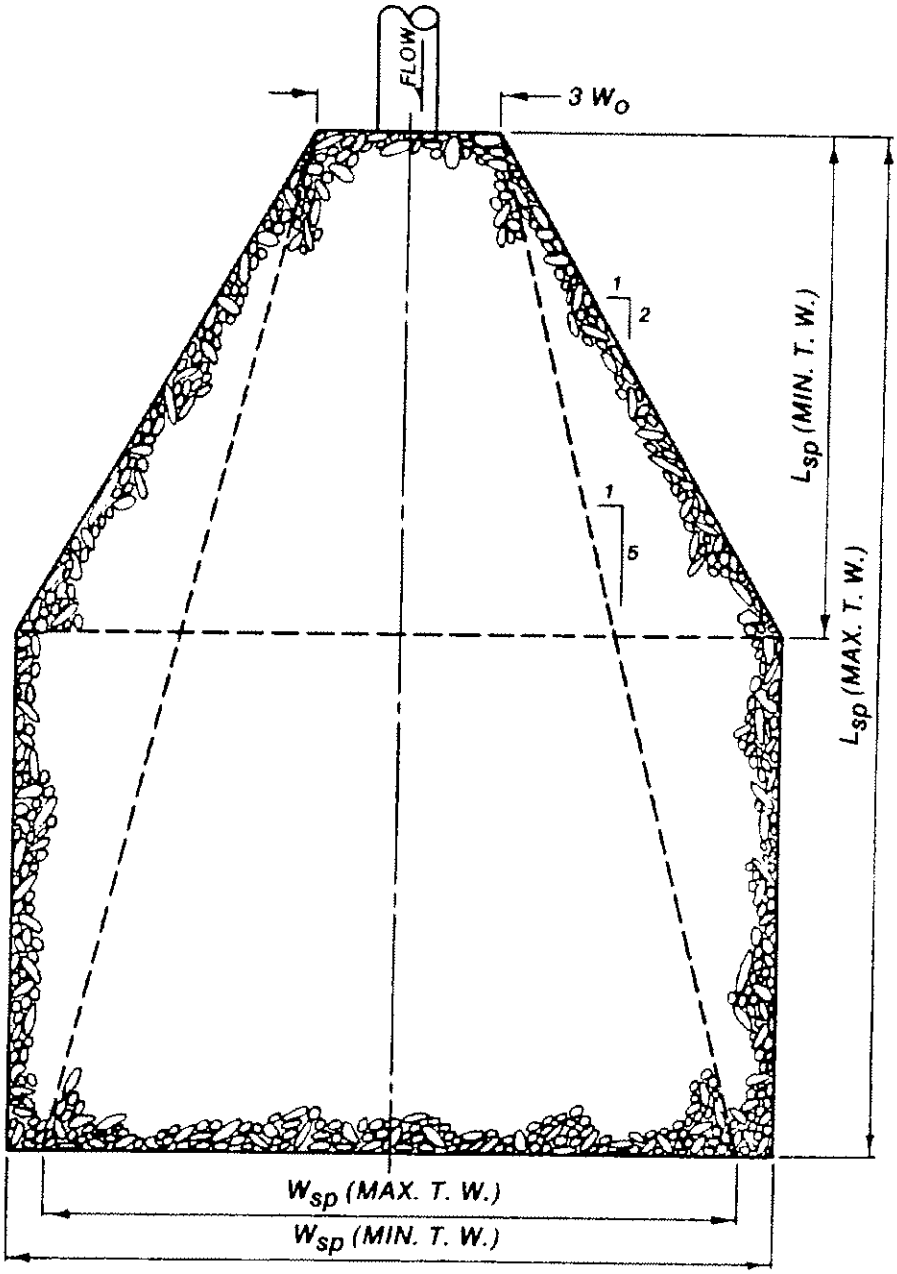



*Figure 5-12. Recommended configuration of riprap blanket subject to minimum and maximum tailwaters.*

*b.* The relative advantage of providing both vertical and lateral expansion downstream of an outlet to permit dissipation of excess kinetic energy in turbulence, rather than direct attack of the boundaries, is shown in figure 5-10. Figure 5-10 indicates that the required size of stone may be reduced considerably if a riprap-lined, preformed scour hole is provided, instead of a horizontal blanket at an elevation essentially the same as the outlet invert. Details of a scheme of riprap protection termed "performed scour hole lined with riprap" are shown in figure 5-13.

# APPENDIX A

# CALCULATIONS

Table
Rating Table for Circular Channel

| Project Description | |
|---|---|
| Project File | c:\haestad\academic\fmw\full pip.fm2 |
| Worksheet | 12" CMP |
| Flow Element | Circular Channel |
| Method | Manning's Formula |
| Solve For | Discharge |

| Constant Data | |
|---|---|
| Mannings Coefficient | 0.024 |
| Depth | 1.00 ft |
| Diameter | 12.00 in |

| Input Data | | | |
|---|---|---|---|
| | Minimum | Maximum | Increment |
| Channel Slope | 0.010000 | 0.100000 | 0.010000 ft/ft |

Rating Table

| Channel Slope (ft/ft) | Discharge (cfs) | Velocity (ft/s) |
|---|---|---|
| 0.010000 | 1.93 | 2.46 |
| 0.020000 | 2.73 | 3.47 |
| 0.030000 | 3.34 | 4.26 |
| 0.040000 | 3.86 | 4.91 |
| 0.050000 | 4.32 | 5.49 |
| 0.060000 | 4.73 | 6.02 |
| 0.070000 | 5.11 | 6.50 |
| 0.080000 | 5.46 | 6.95 |
| 0.090000 | 5.79 | 7.37 |
| 0.100000 | 6.10 | 7.77 |

# Table
## Rating Table for Circular Channel

| Project Description | |
|---|---|
| Project File | c:\haestad\academic\fmw\full pip.fm2 |
| Worksheet | 18" CMP |
| Flow Element | Circular Channel |
| Method | Manning's Formula |
| Solve For | Discharge |

| Constant Data | |
|---|---|
| Mannings Coefficient | 0.024 |
| Depth | 1.50 ft |
| Diameter | 18.00 in |

| Input Data | | | |
|---|---|---|---|
| | Minimum | Maximum | Increment |
| Channel Slope | 0.010000 | 0.100000 | 0.010000 ft/ft |

| Rating Table | | |
|---|---|---|
| Channel Slope (ft/ft) | Discharge (cfs) | Velocity (ft/s) |
| 0.010000 | 5.69 | 3.22 |
| 0.020000 | 8.05 | 4.55 |
| 0.030000 | 9.85 | 5.58 |
| 0.040000 | 11.38 | 6.44 |
| 0.050000 | 12.72 | 7.20 |
| 0.060000 | 13.94 | 7.89 |
| 0.070000 | 15.05 | 8.52 |
| 0.080000 | 16.09 | 9.11 |
| 0.090000 | 17.07 | 9.66 |
| 0.100000 | 17.99 | 10.18 |

Table
Rating Table for Circular Channel

| Project Description | |
|---|---|
| Project File | c:\haestad\academic\fmw\full pip.fm2 |
| Worksheet | 24" CMP |
| Flow Element | Circular Channel |
| Method | Manning's Formula |
| Solve For | Discharge |

| Constant Data | | |
|---|---|---|
| Mannings Coefficient | 0.024 | |
| Depth | 2.00 | ft |
| Diameter | 24.00 | in |

| Input Data | | | |
|---|---|---|---|
| | Minimum | Maximum | Increment |
| Channel Slope | 0.010000 | 0.100000 | 0.010000 ft/ft |

Rating Table

| Channel Slope (ft/ft) | Discharge (cfs) | Velocity (ft/s) |
|---|---|---|
| 0.010000 | 12.25 | 3.90 |
| 0.020000 | 17.33 | 5.52 |
| 0.030000 | 21.22 | 6.76 |
| 0.040000 | 24.51 | 7.80 |
| 0.050000 | 27.40 | 8.72 |
| 0.060000 | 30.01 | 9.55 |
| 0.070000 | 32.42 | 10.32 |
| 0.080000 | 34.66 | 11.03 |
| 0.090000 | 36.76 | 11.70 |
| 0.100000 | 38.75 | 12.33 |

Table
Rating Table for Circular Channel

| Project Description | |
|---|---|
| Project File | c:\haestad\academic\fmw\full pip.fm2 |
| Worksheet | 30" CMP |
| Flow Element | Circular Channel |
| Method | Manning's Formula |
| Solve For | Discharge |

| Constant Data | |
|---|---|
| Mannings Coefficient | 0.024 |
| Depth | 2.50 ft |
| Diameter | 30.00 in |

| Input Data | | | |
|---|---|---|---|
| | Minimum | Maximum | Increment |
| Channel Slope | 0.010000 | 0.100000 | 0.010000 ft/ft |

Rating Table

| Channel Slope (ft/ft) | Discharge (cfs) | Velocity (ft/s) |
|---|---|---|
| 0.010000 | 22.22 | 4.53 |
| 0.020000 | 31.42 | 6.40 |
| 0.030000 | 38.48 | 7.84 |
| 0.040000 | 44.43 | 9.05 |
| 0.050000 | 49.68 | 10.12 |
| 0.060000 | 54.42 | 11.09 |
| 0.070000 | 58.78 | 11.97 |
| 0.080000 | 62.84 | 12.80 |
| 0.090000 | 66.65 | 13.58 |
| 0.100000 | 70.25 | 14.31 |

# Table
## Rating Table for Circular Channel

| Project Description | |
|---|---|
| Project File | c:\haestad\academic\fmw\full pip.fm2 |
| Worksheet | 36" CMP |
| Flow Element | Circular Channel |
| Method | Manning's Formula |
| Solve For | Discharge |

| Constant Data | |
|---|---|
| Mannings Coefficient | 0.024 |
| Depth | 3.00 ft |
| Diameter | 36.00 in |

| Input Data | | | |
|---|---|---|---|
| | Minimum | Maximum | Increment |
| Channel Slope | 0.010000 | 0.100000 | 0.010000 ft/ft |

| Rating Table | | |
|---|---|---|
| Channel Slope (ft/ft) | Discharge (cfs) | Velocity (ft/s) |
| 0.010000 | 36.13 | 5.11 |
| 0.020000 | 51.09 | 7.23 |
| 0.030000 | 62.57 | 8.85 |
| 0.040000 | 72.25 | 10.22 |
| 0.050000 | 80.78 | 11.43 |
| 0.060000 | 88.49 | 12.52 |
| 0.070000 | 95.58 | 13.52 |
| 0.080000 | 102.18 | 14.46 |
| 0.090000 | 108.38 | 15.33 |
| 0.100000 | 114.24 | 16.16 |

Table
Rating Table for Circular Channel

| Project Description | |
|---|---|
| Project File | c:\haestad\academic\fmw\full pip.fm2 |
| Worksheet | 42" CMP |
| Flow Element | Circular Channel |
| Method | Manning's Formula |
| Solve For | Discharge |

| Constant Data | | |
|---|---|---|
| Mannings Coefficient | 0.024 | |
| Depth | 3.50 | ft |
| Diameter | 42.00 | in |

| Input Data | | | |
|---|---|---|---|
| | Minimum | Maximum | Increment |
| Channel Slope | 0.010000 | 0.100000 | 0.010000 ft/ft |

| Rating Table | | |
|---|---|---|
| Channel Slope (ft/ft) | Discharge (cfs) | Velocity (ft/s) |
| 0.010000 | 54.49 | 5.66 |
| 0.020000 | 77.07 | 8.01 |
| 0.030000 | 94.39 | 9.81 |
| 0.040000 | 108.99 | 11.33 |
| 0.050000 | 121.85 | 12.67 |
| 0.060000 | 133.48 | 13.87 |
| 0.070000 | 144.18 | 14.99 |
| 0.080000 | 154.13 | 16.02 |
| 0.090000 | 163.48 | 16.99 |
| 0.100000 | 172.33 | 17.91 |

# Table
## Rating Table for Circular Channel

| Project Description | |
|---|---|
| Project File | c:\haestad\academic\fmw\full pip.fm2 |
| Worksheet | 48" CMP |
| Flow Element | Circular Channel |
| Method | Manning's Formula |
| Solve For | Discharge |

| Constant Data | |
|---|---|
| Mannings Coefficient | 0.024 |
| Depth | 4.00 ft |
| Diameter | 48.00 in |

| Input Data | | | |
|---|---|---|---|
| | Minimum | Maximum | Increment |
| Channel Slope | 0.010000 | 0.100000 | 0.010000 ft/ft |

Rating Table

| Channel Slope (ft/ft) | Discharge (cfs) | Velocity (ft/s) |
|---|---|---|
| 0.010000 | 77.80 | 6.19 |
| 0.020000 | 110.03 | 8.76 |
| 0.030000 | 134.76 | 10.72 |
| 0.040000 | 155.61 | 12.38 |
| 0.050000 | 173.97 | 13.84 |
| 0.060000 | 190.58 | 15.17 |
| 0.070000 | 205.85 | 16.38 |
| 0.080000 | 220.06 | 17.51 |
| 0.090000 | 233.41 | 18.57 |
| 0.100000 | 246.03 | 19.58 |

Table
Rating Table for Circular Channel

| Project Description | |
|---|---|
| Project File | c:\haestad\academic\fmw\full pip.fm2 |
| Worksheet | 54" CMP |
| Flow Element | Circular Channel |
| Method | Manning's Formula |
| Solve For | Discharge |

| Constant Data | |
|---|---|
| Mannings Coefficient | 0.024 |
| Depth | 4.50 ft |
| Diameter | 54.00 in |

| Input Data | | | |
|---|---|---|---|
| | Minimum | Maximum | Increment |
| Channel Slope | 0.010000 | 0.100000 | 0.010000 ft/ft |

Rating Table

| Channel Slope (ft/ft) | Discharge (cfs) | Velocity (ft/s) |
|---|---|---|
| 0.010000 | 106.51 | 6.70 |
| 0.020000 | 150.63 | 9.47 |
| 0.030000 | 184.49 | 11.60 |
| 0.040000 | 213.02 | 13.39 |
| 0.050000 | 238.17 | 14.98 |
| 0.060000 | 260.90 | 16.40 |
| 0.070000 | 281.81 | 17.72 |
| 0.080000 | 301.26 | 18.94 |
| 0.090000 | 319.54 | 20.09 |
| 0.100000 | 336.82 | 21.18 |

# Table
## Rating Table for Circular Channel

| Project Description | |
|---|---|
| Project File | c:\haestad\academic\fmw\full pip.fm2 |
| Worksheet | 60" CMP |
| Flow Element | Circular Channel |
| Method | Manning's Formula |
| Solve For | Discharge |

| Constant Data | |
|---|---|
| Mannings Coefficient | 0.024 |
| Depth | 5.00 ft |
| Diameter | 60.00 in |

| Input Data | Minimum | Maximum | Increment |
|---|---|---|---|
| Channel Slope | 0.010000 | 0.100000 | 0.010000 ft/ft |

Rating Table

| Channel Slope (ft/ft) | Discharge (cfs) | Velocity (ft/s) |
|---|---|---|
| 0.010000 | 141.07 | 7.18 |
| 0.020000 | 199.50 | 10.16 |
| 0.030000 | 244.33 | 12.44 |
| 0.040000 | 282.13 | 14.37 |
| 0.050000 | 315.43 | 16.06 |
| 0.060000 | 345.54 | 17.60 |
| 0.070000 | 373.22 | 19.01 |
| 0.080000 | 398.99 | 20.32 |
| 0.090000 | 423.20 | 21.55 |
| 0.100000 | 446.09 | 22.72 |

## OUTLET PROTECTION
### MINIMUM TAILWATER CONDITION; DEPTH < 0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | Quantities | | | Froude Number Check | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | | | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_a$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 12 | 1.93 | 10.47 | 10 | 13.47 | 13 | 1 | 6 | 65 | 2 | 5 | 0.79 | 2.46 | 0.19 |
| 12 | 2.73 | 11.91 | 12 | 14.91 | 15 | 2 | 6 | 90 | 3 | 7 | 0.79 | 3.48 | 0.38 |
| 12 | 3.34 | 13.01 | 13 | 16.01 | 16 | 2 | 6 | 104 | 4 | 9 | 0.79 | 4.25 | 0.56 |
| 12 | 3.86 | 13.95 | 14 | 16.95 | 17 | 3 | 6 | 119 | 4 | 10 | 0.79 | 4.92 | 0.75 |
| 12 | 4.32 | 14.78 | 15 | 17.78 | 18 | 3 | 6 | 135 | 5 | 11 | 0.79 | 5.50 | 0.94 |
| 12 | 4.73 | 15.51 | 16 | 18.51 | 19 | 4 | 6 | 152 | 6 | 13 | 0.79 | 6.03 | 1.13 |
| 12 | 5.11 | 16.20 | 16 | 19.20 | 19 | 4 | 6 | 152 | 6 | 13 | 0.79 | 6.51 | 1.32 |
| 12 | 5.46 | 16.83 | 17 | 19.83 | 20 | 5 | 7 | 198 | 7 | 16 | 0.79 | 6.96 | 1.50 |
| 12 | 5.79 | 17.42 | 17 | 20.42 | 20 | 5 | 8 | 227 | 8 | 19 | 0.79 | 7.38 | 1.69 |
| 12 | 6.10 | 17.98 | 18 | 20.98 | 21 | 5 | 8 | 252 | 9 | 21 | 0.79 | 7.77 | 1.88 |

## OUTLET PROTECTION
### MAXIMUM TAILWATER CONDITION; DEPTH ≥0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | Quantities | | | Froude Number Check | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | | | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_a$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 12 | 1.93 | 5.79 | 6 | 5.32 | 5 | 1 | 6 | 15 | 1 | 1 | 0.79 | 2.46 | 0.19 |
| 12 | 2.73 | 8.19 | 8 | 6.28 | 6 | 1 | 6 | 24 | 1 | 2 | 0.79 | 3.48 | 0.38 |
| 12 | 3.34 | 10.02 | 10 | 7.01 | 7 | 1 | 6 | 35 | 1 | 3 | 0.79 | 4.25 | 0.56 |
| 12 | 3.86 | 11.58 | 12 | 7.63 | 8 | 2 | 6 | 48 | 2 | 4 | 0.79 | 4.92 | 0.75 |
| 12 | 4.32 | 12.96 | 13 | 8.18 | 8 | 2 | 6 | 52 | 2 | 4 | 0.79 | 5.50 | 0.94 |
| 12 | 4.73 | 14.19 | 14 | 8.68 | 9 | 2 | 6 | 63 | 2 | 5 | 0.79 | 6.03 | 1.13 |
| 12 | 5.11 | 15.33 | 15 | 9.13 | 9 | 2 | 6 | 68 | 3 | 6 | 0.79 | 6.51 | 1.32 |
| 12 | 5.46 | 16.38 | 16 | 9.55 | 10 | 2 | 6 | 80 | 3 | 7 | 0.79 | 6.96 | 1.50 |
| 12 | 5.79 | 17.37 | 17 | 9.95 | 10 | 3 | 6 | 85 | 3 | 7 | 0.79 | 7.38 | 1.69 |
| 12 | 6.10 | 18.30 | 18 | 10.32 | 10 | 3 | 6 | 90 | 3 | 7 | 0.79 | 7.77 | 1.88 |

## OUTLET PROTECTION
### MINIMUM TAILWATER CONDITION; DEPTH < 0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | | Quantities | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | Froude Number Check | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_a$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 18 | 5.7 | 12.58 | 13 | 17.08 | 11 | 2 | 6 | 72 | 3 | 6 | 1.77 | 3.22 | 0.21 |
| 18 | 8.1 | 14.89 | 15 | 19.39 | 19 | 3 | 6 | 143 | 5 | 12 | 1.77 | 4.56 | 0.43 |
| 18 | 10 | 16.65 | 17 | 21.15 | 21 | 4 | 6 | 179 | 7 | 15 | 1.77 | 5.58 | 0.64 |
| 18 | 11 | 18.15 | 18 | 22.65 | 23 | 5 | 7 | 242 | 9 | 20 | 1.77 | 6.44 | 0.86 |
| 18 | 13 | 19.46 | 20 | 23.96 | 24 | 6 | 8 | 320 | 12 | 26 | 1.77 | 7.20 | 1.07 |
| 18 | 14 | 20.66 | 21 | 25.16 | 25 | 6 | 9 | 394 | 15 | 32 | 1.77 | 7.89 | 1.29 |
| 18 | 15 | 21.75 | 22 | 26.25 | 26 | 7 | 11 | 524 | 19 | 43 | 1.77 | 8.52 | 1.50 |
| 18 | 16 | 22.76 | 23 | 27.26 | 27 | 8 | 11 | 569 | 21 | 47 | 1.77 | 9.11 | 1.72 |
| 18 | 17 | 23.73 | 24 | 28.23 | 28 | 8 | 12 | 672 | 25 | 55 | 1.77 | 9.66 | 1.93 |
| 18 | 18 | 24.63 | 25 | 29.13 | 29 | 9 | 13 | 785 | 29 | 65 | 1.77 | 10.19 | 2.15 |

## OUTLET PROTECTION
### MAXIMUM TAILWATER CONDITION; DEPTH ≥0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | | Quantities | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | Froude Number Check | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_a$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 18 | 5.7 | 9.29 | 9 | 8.22 | 8 | 1 | 6 | 36 | 1 | 3 | 1.77 | 3.22 | 0.21 |
| 18 | 8.1 | 13.15 | 13 | 9.76 | 10 | 2 | 6 | 65 | 2 | 5 | 1.77 | 4.56 | 0.43 |
| 18 | 10 | 16.08 | 16 | 10.93 | 11 | 2 | 6 | 88 | 3 | 7 | 1.77 | 5.58 | 0.64 |
| 18 | 11 | 18.58 | 19 | 11.93 | 11 | 2 | 6 | 105 | 4 | 9 | 1.77 | 6.44 | 0.86 |
| 18 | 13 | 20.77 | 21 | 12.81 | 13 | 3 | 6 | 137 | 5 | 11 | 1.77 | 7.20 | 1.07 |
| 18 | 14 | 22.76 | 23 | 13.61 | 14 | 3 | 6 | 161 | 6 | 13 | 1.77 | 7.89 | 1.29 |
| 18 | 15 | 24.58 | 25 | 14.33 | 14 | 4 | 6 | 175 | 6 | 14 | 1.77 | 8.52 | 1.50 |
| 18 | 16 | 26.27 | 26 | 15.01 | 15 | 4 | 6 | 195 | 7 | 16 | 1.77 | 9.11 | 1.72 |
| 18 | 17 | 27.88 | 28 | 15.65 | 16 | 4 | 6 | 224 | 8 | 18 | 1.77 | 9.66 | 1.93 |
| 18 | 18 | 29.38 | 29 | 16.25 | 16 | 4 | 7 | 271 | 10 | 22 | 1.77 | 10.19 | 2.15 |

## OUTLET PROTECTION
### MINIMUM TAILWATER CONDITION; DEPTH < 0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | Quantities | | | Froude Number Check | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | | | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_a$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 24 | 12 | 14.80 | 15 | 20.80 | 21 | 3 | 6 | 158 | 6 | 13 | 3.14 | 3.90 | 0.24 |
| 24 | 17 | 18.03 | 18 | 24.03 | 24 | 4 | 6 | 216 | 8 | 18 | 3.14 | 5.52 | 0.47 |
| 24 | 21 | 20.50 | 20 | 26.50 | 26 | 6 | 8 | 347 | 13 | 29 | 3.14 | 6.76 | 0.71 |
| 24 | 25 | 23.17 | 23 | 29.17 | 29 | 7 | 11 | 611 | 23 | 50 | 3.14 | 8.09 | 1.02 |
| 24 | 27 | 24.44 | 24 | 30.44 | 30 | 8 | 12 | 720 | 27 | 59 | 3.14 | 8.73 | 1.18 |
| 24 | 30 | 26.10 | 26 | 32.10 | 32 | 9 | 13 | 901 | 33 | 74 | 3.14 | 9.56 | 1.42 |
| 24 | 32 | 27.63 | 28 | 33.63 | 34 | 10 | 15 | 1,190 | 44 | 98 | 3.14 | 10.32 | 1.66 |
| 24 | 35 | 29.06 | 29 | 35.06 | 35 | 11 | 16 | 1,353 | 50 | 112 | 3.14 | 11.04 | 1.89 |
| 24 | 37 | 30.39 | 30 | 36.39 | 36 | 12 | 18 | 1,620 | 60 | 134 | 3.14 | 11.71 | 2.13 |
| 24 | 39 | 31.66 | 32 | 37.66 | 38 | 13 | 19 | 1,925 | 71 | 159 | 3.14 | 12.34 | 2.36 |

## OUTLET PROTECTION
### MAXIMUM TAILWATER CONDITION; DEPTH ≥0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | Quantities | | | Froude Number Check | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | | | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_a$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 24 | 12 | 12.99 | 13 | 11.20 | 11 | 1 | 6 | 72 | 3 | 6 | 3.14 | 3.90 | 0.24 |
| 24 | 17 | 18.38 | 18 | 13.35 | 13 | 2 | 6 | 117 | 4 | 10 | 3.14 | 5.52 | 0.47 |
| 24 | 21 | 22.51 | 23 | 15.00 | 15 | 3 | 6 | 173 | 6 | 14 | 3.14 | 6.76 | 0.71 |
| 24 | 25 | 26.95 | 27 | 16.78 | 17 | 4 | 6 | 230 | 9 | 19 | 3.14 | 8.09 | 1.02 |
| 24 | 27 | 29.06 | 29 | 17.62 | 18 | 4 | 6 | 261 | 10 | 22 | 3.14 | 8.73 | 1.18 |
| 24 | 30 | 31.83 | 32 | 18.73 | 19 | 5 | 7 | 355 | 13 | 29 | 3.14 | 9.56 | 1.42 |
| 24 | 32 | 34.39 | 34 | 19.75 | 20 | 5 | 8 | 453 | 17 | 37 | 3.14 | 10.32 | 1.66 |
| 24 | 35 | 36.76 | 37 | 20.70 | 21 | 5 | 8 | 518 | 19 | 43 | 3.14 | 11.04 | 1.89 |
| 24 | 37 | 38.99 | 39 | 21.60 | 22 | 6 | 9 | 644 | 24 | 53 | 3.14 | 11.71 | 2.13 |
| 24 | 39 | 41.10 | 41 | 22.44 | 22 | 6 | 9 | 677 | 25 | 56 | 3.14 | 12.34 | 2.36 |

## OUTLET PROTECTION
### MINIMUM TAILWATER CONDITION; DEPTH < 0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | Quantities | | | Froude Number Check | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | | | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_s$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 30 | 22 | 17.12 | 17 | 24.62 | 25 | 4 | 6 | 213 | 8 | 18 | 4.91 | 4.53 | 0.25 |
| 30 | 31 | 21.31 | 21 | 28.81 | 29 | 6 | 9 | 457 | 17 | 38 | 4.91 | 6.40 | 0.51 |
| 30 | 38 | 24.52 | 25 | 32.02 | 32 | 7 | 11 | 733 | 27 | 61 | 4.91 | 7.84 | 0.76 |
| 30 | 44 | 27.23 | 27 | 34.73 | 35 | 9 | 14 | 1,103 | 41 | 91 | 4.91 | 9.06 | 1.02 |
| 30 | 50 | 29.62 | 30 | 37.12 | 37 | 10 | 16 | 1,480 | 55 | 122 | 4.91 | 10.13 | 1.27 |
| 30 | 54 | 31.78 | 32 | 39.28 | 39 | 12 | 18 | 1,872 | 69 | 154 | 4.91 | 11.09 | 1.53 |
| 30 | 59 | 33.77 | 34 | 41.27 | 41 | 13 | 20 | 2,323 | 86 | 192 | 4.91 | 11.98 | 1.78 |
| 30 | 63 | 35.62 | 36 | 43.12 | 43 | 14 | 21 | 2,709 | 100 | 223 | 4.91 | 12.81 | 2.04 |
| 30 | 67 | 37.35 | 37 | 44.85 | 45 | 15 | 23 | 3,191 | 118 | 263 | 4.91 | 13.58 | 2.29 |
| 30 | 70 | 38.98 | 39 | 46.48 | 47 | 17 | 25 | 3,618 | 134 | 316 | 4.91 | 14.32 | 2.55 |

## OUTLET PROTECTION
### MAXIMUM TAILWATER CONDITION; DEPTH ≥0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | Quantities | | | Froude Number Check | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | | | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_s$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 30 | 22 | 16.86 | 17 | 14.25 | 14 | 2 | 6 | 119 | 4 | 10 | 4.91 | 4.53 | 0.25 |
| 30 | 31 | 23.85 | 24 | 17.04 | 17 | 3 | 6 | 204 | 8 | 17 | 4.91 | 6.40 | 0.51 |
| 30 | 38 | 29.20 | 29 | 19.18 | 19 | 4 | 6 | 276 | 10 | 23 | 4.91 | 7.84 | 0.76 |
| 30 | 44 | 33.72 | 34 | 20.99 | 21 | 5 | 7 | 417 | 15 | 34 | 4.91 | 9.06 | 1.02 |
| 30 | 50 | 37.70 | 38 | 22.58 | 23 | 5 | 8 | 583 | 22 | 48 | 4.91 | 10.13 | 1.27 |
| 30 | 54 | 41.30 | 41 | 24.02 | 24 | 6 | 9 | 738 | 27 | 61 | 4.91 | 11.09 | 1.53 |
| 30 | 59 | 44.61 | 45 | 25.34 | 25 | 7 | 10 | 938 | 35 | 77 | 4.91 | 11.98 | 1.78 |
| 30 | 63 | 47.69 | 48 | 26.58 | 27 | 7 | 11 | 1,188 | 44 | 98 | 4.91 | 12.81 | 2.04 |
| 30 | 67 | 50.58 | 51 | 27.73 | 28 | 8 | 12 | 1,428 | 53 | 118 | 4.91 | 13.58 | 2.29 |
| 30 | 70 | 53.32 | 53 | 28.80 | 29 | 8 | 12 | 1,637 | 61 | 137 | 4.91 | 14.32 | 2.55 |

## OUTLET PROTECTION
### MINIMUM TAILWATER CONDITION; DEPTH < 0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | Quantities | | | Froude Number Check | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | | | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_a$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 36 | 36 | 19.52 | 20 | 28.52 | 29 | 5 | 7 | 338 | 13 | 28 | 7.07 | 5.11 | 0.27 |
| 36 | 51 | 24.70 | 25 | 33.70 | 34 | 7 | 11 | 779 | 29 | 64 | 7.07 | 7.23 | 0.54 |
| 36 | 63 | 28.67 | 29 | 37.67 | 38 | 9 | 14 | 1,286 | 48 | 106 | 7.07 | 8.86 | 0.81 |
| 36 | 72 | 32.03 | 32 | 41.03 | 41 | 11 | 17 | 1,859 | 69 | 153 | 7.07 | 10.23 | 1.08 |
| 36 | 81 | 34.98 | 35 | 43.98 | 44 | 13 | 20 | 2,567 | 95 | 212 | 7.07 | 11.43 | 1.35 |
| 36 | 88 | 37.65 | 38 | 46.65 | 47 | 15 | 22 | 3,274 | 121 | 270 | 7.07 | 12.53 | 1.62 |
| 36 | 96 | 40.11 | 40 | 49.11 | 49 | 16 | 24 | 3,920 | 145 | 323 | 7.07 | 13.53 | 1.89 |
| 36 | 102 | 42.40 | 42 | 51.40 | 51 | 18 | 27 | 4,820 | 179 | 398 | 7.07 | 14.46 | 2.17 |
| 36 | 108 | 44.54 | 45 | 53.54 | 54 | 19 | 29 | 5,873 | 218 | 484 | 7.07 | 15.34 | 2.44 |
| 36 | 114 | 46.67 | 46 | [illegible] | 55 | 21 | 31 | [illegible] | [illegible] | [illegible] | 7.07 | [illegible] | 2.71 |

## OUTLET PROTECTION
### MAXIMUM TAILWATER CONDITION; DEPTH ≥0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | Quantities | | | Froude Number Check | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | | | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_a$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 36 | 36 | 20.86 | 21 | 17.34 | 17 | 2 | 6 | 179 | 7 | 15 | 7.07 | 5.11 | 0.27 |
| 36 | 51 | 29.50 | 30 | 20.80 | 21 | 4 | 6 | 315 | 12 | 26 | 7.07 | 7.23 | 0.54 |
| 36 | 63 | 36.12 | 36 | 23.45 | 23 | 5 | 7 | 483 | 18 | 40 | 7.07 | 8.86 | 0.81 |
| 36 | 72 | 41.71 | 42 | 25.69 | 26 | 6 | 8 | 728 | 27 | 60 | 7.07 | 10.23 | 1.08 |
| 36 | 81 | 46.64 | 47 | 27.66 | 28 | 7 | 10 | 1,097 | 41 | 90 | 7.07 | 11.43 | 1.35 |
| 36 | 88 | 51.09 | 51 | 29.44 | 29 | 7 | 11 | 1,356 | 50 | 112 | 7.07 | 12.53 | 1.62 |
| 36 | 96 | 55.18 | 55 | 31.07 | 31 | 8 | 12 | 1,705 | 63 | 141 | 7.07 | 13.53 | 1.89 |
| 36 | 102 | 58.99 | 59 | 32.60 | 33 | 9 | 13 | 2,109 | 78 | 174 | 7.07 | 14.46 | 2.17 |
| 36 | 108 | 62.57 | 63 | 34.03 | 34 | 10 | 14 | 2,499 | 93 | 206 | 7.07 | 15.34 | 2.44 |
| 36 | 114 | 66.36 | 66 | [illegible] | 35 | 10 | 15 | [illegible] | 107 | [illegible] | 7.07 | [illegible] | 2.71 |

## OUTLET PROTECTION
### MINIMUM TAILWATER CONDITION; DEPTH < 0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | Quantities | | | Froude Number Check | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | | | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_a$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 42 | 54 | 21.98 | 22 | 32.48 | 32 | 5 | 8 | 469 | 17 | 39 | 9.62 | 5.67 | 0.28 |
| 42 | 77 | 28.19 | 28 | 38.69 | 39 | 9 | 13 | 1,183 | 44 | 98 | 9.62 | 8.01 | 0.57 |
| 42 | 94 | 32.95 | 33 | 43.45 | 43 | 11 | 17 | 2,010 | 74 | 166 | 9.62 | 9.82 | 0.85 |
| 42 | 109 | 36.96 | 37 | 47.46 | 47 | 14 | 20 | 2,898 | 107 | 239 | 9.62 | 11.33 | 1.14 |
| 42 | 122 | 40.50 | 40 | 51.00 | 51 | 16 | 23 | 3,910 | 145 | 323 | 9.62 | 12.67 | 1.42 |
| 42 | 133 | 43.69 | 44 | 54.19 | 54 | 18 | 27 | 5,346 | 198 | 441 | 9.62 | 13.88 | 1.71 |
| 42 | 144 | 46.63 | 47 | 57.13 | 57 | 20 | 29 | 6,474 | 240 | 534 | 9.62 | 14.99 | 1.99 |
| 42 | 154 | 49.37 | 49 | 59.87 | 60 | 21 | 32 | 7,840 | 290 | 647 | 9.62 | 16.03 | 2.28 |
| 42 | 163 | 51.94 | 52 | 62.44 | 63 | 23 | 35 | 9,463 | 350 | 778 | 9.62 | 17.00 | 2.56 |
| 42 | 172 | 54.37 | 54 | 64.87 | 65 | 24 | 37 | 11,323 | 419 | 931 | 9.62 | 17.92 | 2.85 |

## OUTLET PROTECTION
### MAXIMUM TAILWATER CONDITION; DEPTH ≥0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | Quantities | | | Froude Number Check | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | | | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_a$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 42 | 54 | 24.97 | 25 | 20.49 | 20 | 3 | 6 | 250 | 9 | 21 | 9.62 | 5.67 | 0.28 |
| 42 | 77 | 35.31 | 35 | 24.62 | 25 | 4 | 6 | 438 | 16 | 36 | 9.62 | 8.01 | 0.57 |
| 42 | 94 | 43.25 | 43 | 27.80 | 28 | 6 | 8 | 803 | 30 | 66 | 9.62 | 9.82 | 0.85 |
| 42 | 109 | 49.94 | 50 | 30.47 | 30 | 7 | 10 | 1,250 | 46 | 103 | 9.62 | 11.33 | 1.14 |
| 42 | 122 | 55.83 | 56 | 32.83 | 33 | 8 | 12 | 1,848 | 68 | 152 | 9.62 | 12.67 | 1.42 |
| 42 | 133 | 61.16 | 61 | 34.96 | 35 | 9 | 13 | 2,313 | 86 | 191 | 9.62 | 13.88 | 1.71 |
| 42 | 144 | 66.06 | 66 | 36.92 | 37 | 10 | 15 | 3,053 | 113 | 252 | 9.62 | 14.99 | 1.99 |
| 42 | 154 | 70.62 | 71 | 38.75 | 39 | 11 | 16 | 3,692 | 137 | 305 | 9.62 | 16.03 | 2.28 |
| 42 | 163 | 74.90 | 75 | 40.48 | 40 | 12 | 17 | 4,296 | 159 | 354 | 9.62 | 17.00 | 2.56 |
| 42 | 172 | 79.06 | 79 | 42.06 | 42 | 12 | 19 | 5,253 | 195 | 433 | 9.62 | 17.92 | 2.85 |

## OUTLET PROTECTION
### MINIMUM TAILWATER CONDITION; DEPTH < 0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | Quantities | | | Froude Number Check | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | | | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_a$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 48 | 78 | 24.51 | 25 | 36.51 | 37 | 6 | 9 | 694 | 26 | 57 | 12.56 | 6.19 | 0.30 |
| 48 | 110 | 31.76 | 32 | 43.76 | 44 | 10 | 15 | 1,760 | 65 | 145 | 12.56 | 8.76 | 0.60 |
| 48 | 135 | 37.32 | 37 | 49.32 | 49 | 13 | 20 | 3,022 | 112 | 249 | 12.56 | 10.73 | 0.89 |
| 48 | 156 | 42.01 | 42 | 54.01 | 54 | 16 | 24 | 4,536 | 168 | 374 | 12.56 | 12.39 | 1.19 |
| 48 | 174 | 46.14 | 46 | 58.14 | 58 | 18 | 28 | 6,225 | 231 | 514 | 12.56 | 13.85 | 1.49 |
| 48 | 191 | 49.88 | 50 | 61.88 | 62 | 21 | 31 | 8,008 | 297 | 661 | 12.56 | 15.17 | 1.79 |
| 48 | 206 | 53.32 | 53 | 65.32 | 65 | 23 | 35 | 10,048 | 372 | 829 | 12.56 | 16.39 | 2.09 |
| 48 | 220 | 56.51 | 57 | 68.51 | 69 | 25 | 38 | 12,455 | 461 | 1027 | 12.56 | 17.52 | 2.38 |
| 48 | 233 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 12.56 | [illegible] | 2.66 |
| 48 | 246 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 12.56 | [illegible] | 2.95 |

## OUTLET PROTECTION
### MAXIMUM TAILWATER CONDITION; DEPTH ≥0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | Quantities | | | Froude Number Check | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | | | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_a$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 48 | 78 | 29.18 | 29 | 23.67 | 24 | 3 | 6 | 348 | 13 | 29 | 12.56 | 6.19 | 0.30 |
| 48 | 110 | 41.26 | 41 | 28.50 | 28 | 5 | 8 | 765 | 28 | 63 | 12.56 | 8.76 | 0.60 |
| 48 | 135 | 50.54 | 51 | 32.21 | 32 | 7 | 10 | 1,360 | 50 | 112 | 12.56 | 10.73 | 0.89 |
| 48 | 156 | 58.50 | 58 | 35.40 | 35 | 8 | 12 | 2,030 | 75 | 167 | 12.56 | 12.42 | 1.20 |
| 48 | 174 | 65.24 | 66 | 38.10 | 38 | 9 | 14 | 2,926 | 108 | 241 | 12.56 | 13.85 | 1.49 |
| 48 | 191 | 71.47 | 71 | 40.59 | 41 | 10 | 16 | 3,881 | 144 | 320 | 12.56 | 15.17 | 1.79 |
| 48 | 206 | 77.19 | 77 | 42.88 | 43 | 12 | 17 | 4,691 | 174 | 387 | 12.56 | 16.39 | 2.09 |
| 48 | 220 | 82.52 | 83 | 45.01 | 45 | 13 | 19 | 5,914 | 219 | 488 | 12.56 | 17.52 | 2.38 |
| 48 | 233 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 12.56 | [illegible] | 2.66 |
| 48 | 246 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 12.56 | [illegible] | 2.95 |

## OUTLET PROTECTION
### MINIMUM TAILWATER CONDITION; DEPTH < 0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | Quantities | | | Froude Number Check | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | | | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_a$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 54 | 107 | 27.08 | 27 | 40.58 | 41 | 7 | 11 | 1,015 | 38 | 84 | 15.90 | 6.70 | 0.31 |
| 54 | 151 | 35.40 | 65 | 48.90 | 49 | 12 | 17 | 4,512 | 167 | 372 | 15.90 | 9.48 | 0.62 |
| 54 | 184 | 41.79 | 42 | 55.29 | 55 | 15 | 23 | 4,428 | 164 | 365 | 15.90 | 11.61 | 0.93 |
| 54 | 213 | 47.17 | 47 | 60.67 | 61 | 18 | 27 | 6,451 | 239 | 532 | 15.90 | 13.40 | 1.24 |
| 54 | 238 | 51.91 | 52 | 65.41 | 65 | 21 | 32 | 9,013 | 334 | 744 | 15.90 | 14.98 | 1.55 |
| 54 | 261 | 56.20 | 56 | 69.70 | 70 | 24 | 36 | 11,760 | 436 | 970 | 15.90 | 16.41 | 1.86 |
| 54 | 282 | 60.14 | 60 | 73.64 | 74 | 27 | 40 | 14,800 | 548 | 1221 | 15.90 | 17.73 | 2.17 |
| 54 | 301 | 63.81 | 64 | 77.31 | 77 | 29 | 44 | 18,069 | 669 | 1491 | 15.90 | 18.95 | 2.48 |
| 54 | 320 | 67.25 | 67 | 80.75 | 81 | 31 | 47 | 21,250 | 787 | 1754 | 15.90 | 20.10 | 2.79 |
| 54 | 337 | 70.51 | 71 | 84.01 | 84 | 34 | 51 | 25,347 | 939 | 2091 | 15.90 | 21.18 | 3.10 |

## OUTLET PROTECTION
### MAXIMUM TAILWATER CONDITION; DEPTH ≥0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | Quantities | | | Froude Number Check | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | | | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_a$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 54 | 107 | 33.47 | 33 | 26.89 | 27 | 4 | 6 | 446 | 17 | 37 | 15.90 | 6.70 | 0.31 |
| 54 | 151 | 47.34 | 47 | 32.44 | 32 | 6 | 9 | 1,128 | 42 | 93 | 15.90 | 9.48 | 0.62 |
| 54 | 184 | 57.98 | 58 | 36.69 | 37 | 8 | 11 | 1,967 | 73 | 162 | 15.90 | 11.61 | 0.93 |
| 54 | 213 | 66.95 | 67 | 40.28 | 40 | 9 | 14 | 3,127 | 116 | 258 | 15.90 | 13.40 | 1.24 |
| 54 | 238 | 74.85 | 75 | 43.44 | 43 | 11 | 16 | 4,300 | 159 | 355 | 15.90 | 14.98 | 1.55 |
| 54 | 261 | 81.99 | 82 | 46.30 | 46 | 12 | 18 | 5,658 | 210 | 467 | 15.90 | 16.41 | 1.86 |
| 54 | 282 | 88.56 | 89 | 48.93 | 49 | 13 | 20 | 7,268 | 269 | 600 | 15.90 | 17.73 | 2.17 |
| 54 | 301 | 94.68 | 95 | 51.37 | 51 | 15 | 22 | 8,883 | 329 | 733 | 15.90 | 18.95 | 2.48 |
| 54 | 320 | 100.42 | 100 | 53.67 | 54 | 16 | 24 | 10,501 | 389 | 866 | 15.90 | 20.10 | 2.79 |
| 54 | 337 | 105.85 | 106 | 55.84 | 56 | 17 | 26 | 12,347 | 457 | 1018 | 15.90 | 21.18 | 3.10 |

## OUTLET PROTECTION
### MINIMUM TAILWATER CONDITION; DEPTH < 0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | Quantities | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | Froude Number Check | | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_s$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 60 | 141 | 29.71 | 30 | 44.71 | 45 | 8 | 12 | 1,350 | 50 | 111 | 19.63 | 7.19 | 0.32 |
| 60 | 200 | 39.12 | 39 | 54.12 | 54 | 13 | 20 | 3,510 | 130 | 290 | 19.63 | 10.17 | 0.64 |
| 60 | 244 | 46.34 | 46 | 61.34 | 61 | 17 | 26 | 6,080 | 225 | 502 | 19.63 | 12.45 | 0.96 |
| 60 | 282 | 52.42 | 53 | 67.42 | 67 | 21 | 31 | 9,173 | 340 | 757 | 19.63 | 14.38 | 1.28 |
| 60 | 315 | 57.78 | 58 | 72.78 | 73 | 24 | 36 | 12,702 | 470 | 1048 | 19.63 | 16.07 | 1.60 |
| 60 | 346 | 62.63 | 63 | 77.63 | 78 | 27 | 41 | 16,790 | 622 | 1385 | 19.63 | 17.61 | 1.93 |
| 60 | 373 | 67.09 | 67 | 82.09 | 82 | 30 | 45 | 20,603 | 763 | 1700 | 19.63 | 19.02 | 2.25 |
| 60 | 399 | 71.65 | 71 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 19.63 | [illegible] | 2.57 |
| 60 | 423 | 75.13 | 75 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 19.63 | [illegible] | 2.89 |
| 60 | 446 | 78.42 | 78 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 19.63 | 22.78 | 3.21 |

## OUTLET PROTECTION
### MAXIMUM TAILWATER CONDITION; DEPTH ≥0.5 (PIPE DIAMETER)

| PIPE | | RIPRAP APRON DIMENSIONS | | | | | | Quantities | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | Froude Number Check | | |
| DIAMETER Do (in) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_s$ (inches) | V (cf) | V (cy) | V (tons) | A (sf) | v (ft/sec) | F |
| 60 | 141 | 37.85 | 38 | 30.14 | 30 | 4 | 6 | 570 | 21 | 47 | 19.63 | 7.19 | 0.32 |
| 60 | 200 | 53.53 | 54 | 36.41 | 36 | 7 | 10 | 1,620 | 60 | 134 | 19.63 | 10.17 | 0.64 |
| 60 | 244 | 65.56 | 66 | 41.22 | 41 | 9 | 13 | 2,932 | 109 | 242 | 19.63 | 12.45 | 0.96 |
| 60 | 282 | 75.70 | 76 | 45.28 | 45 | 10 | 16 | 4,560 | 169 | 376 | 19.63 | 14.38 | 1.28 |
| 60 | 315 | 84.64 | 85 | 48.86 | 49 | 12 | 18 | 6,248 | 231 | 515 | 19.63 | 16.07 | 1.60 |
| 60 | 346 | 92.72 | 93 | 52.09 | 52 | 14 | 21 | 8,463 | 313 | 698 | 19.63 | 17.61 | 1.93 |
| 60 | 373 | 100.15 | 100 | 55.06 | 55 | 15 | 23 | 10,542 | 390 | 870 | 19.63 | 19.02 | 2.25 |
| 60 | 399 | 107.06 | 107 | 57.88 | 58 | 17 | 24 | [illegible] | 479 | 1067 | 19.63 | 20.35 | 2.57 |
| 60 | 420 | 113.56 | 114 | 60.42 | 60 | 18 | 27 | 15,390 | 570 | 1270 | 19.63 | 21.56 | 2.89 |
| 60 | 446 | 119.70 | 120 | 62.86 | 63 | 19 | 28 | [illegible] | [illegible] | [illegible] | 19.63 | 22.78 | 3.21 |

OUTLET PROTECTION
FROUDE NUMBER = 1.0
ROCK RIPRAP APRON

| PIPE | | | | DIMENSIONS | | | | | | Quantities | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | FILTER FABRIC AREA |
| DIAMETER Do (in) | VELOCITY v (cfs) | AREA a (sf) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_a$ (inches) | V (cf) | V (cy) | V (tons) | A (sy) |
| 12 | 5.67 | 0.79 | 4.45 | 15.02 | 15 | 18.02 | 18 | 4 | 6 | 135 | 5 | 11 | 30 |
| 18 | 6.95 | 1.77 | 12.28 | 19.03 | 19 | 23.53 | 24 | 5 | 8 | 304 | 11 | 25 | 51 |
| 24 | 8.02 | 3.14 | 25.20 | 23.04 | 23 | 29.04 | 29 | 7 | 11 | 611 | 23 | 50 | 74 |
| 30 | 8.97 | 4.91 | 44.02 | 27.05 | 27 | 34.55 | 35 | 9 | 13 | 1,024 | 38 | 84 | 105 |
| 36 | 9.83 | 7.07 | 69.44 | 31.05 | 31 | 40.05 | 40 | 11 | 16 | 1,653 | 61 | 136 | 138 |
| 42 | 10.62 | 9.62 | 102.09 | 35.06 | 35 | 45.56 | 46 | 12 | 19 | 2,549 | 94 | 210 | 179 |
| 48 | 11.35 | 12.56 | 142.54 | 39.07 | 39 | 51.07 | 51 | 14 | 21 | 3,481 | 129 | 287 | 221 |
| 54 | 12.04 | 15.90 | 191.35 | 43.08 | 43 | 56.58 | 57 | 16 | 24 | 4,902 | 182 | 404 | 272 |
| 60 | 12.69 | 19.63 | 249.01 | 47.09 | 47 | 62.09 | 62 | 18 | 26 | 6,314 | 234 | 521 | 324 |
| 66 | 13.31 | 23.75 | 316.01 | 51.10 | 51 | 67.60 | 68 | 19 | 29 | 8,381 | 310 | 691 | 385 |
| 72 | 13.90 | 28.26 | 392.80 | 55.11 | 55 | 73.11 | 73 | 21 | 32 | 10,707 | 397 | 883 | 446 |

OUTLET PROTECTION
FROUDE NUMBER = 2.5
ROCK RIPRAP APRON

| PIPE | | | | DIMENSIONS | | | | | | Quantities | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | LENGTH (actual) | LENGTH (rounded to nearest 1' increment) | WIDTH (actual) | WIDTH (rounded to nearest 1' increment) | ROCK SIZE (based on horizontal blanket) | DEPTH | VOLUME | VOLUME | WEIGHT (165 lb/cf) | FILTER FABRIC AREA |
| DIAMETER Do (in) | VELOCITY v (cfs) | AREA A (sf) | DISCHARGE Q (cfs) | $L_{sp}$ (ft) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_a$ (inches) | V (cf) | V (cy) | V (tons) | A (sy) |
| 12 | 8.97 | 0.79 | 7.04 | 21.13 | 21 | 11.45 | 11 | 3 | 6 | 116 | 4 | 10 | 26 |
| 18 | 10.99 | 1.77 | 19.41 | 31.69 | 32 | 17.18 | 17 | 5 | 7 | 317 | 12 | 26 | 60 |
| 24 | 12.69 | 3.14 | 39.84 | 42.26 | 42 | 22.90 | 23 | 7 | 10 | 805 | 30 | 66 | 107 |
| 30 | 14.19 | 4.91 | 69.60 | 52.82 | 53 | 28.63 | 29 | 8 | 12 | 1,537 | 57 | 127 | 171 |
| 36 | 15.54 | 7.07 | 109.79 | 63.39 | 64 | 34.36 | 34 | 10 | 15 | 2,720 | 101 | 224 | 242 |
| 42 | 16.79 | 9.62 | 161.41 | 73.95 | 74 | 40.08 | 40 | 11 | 17 | 4,193 | 155 | 346 | 329 |
| 48 | 17.94 | 12.56 | 225.38 | 84.52 | 85 | 45.81 | 46 | 13 | 20 | 6,517 | 241 | 538 | 434 |
| 54 | 19.03 | 15.90 | 302.55 | 95.08 | 95 | 51.53 | 52 | 15 | 22 | 9,057 | 335 | 747 | 549 |
| 60 | 20.06 | 19.63 | 393.72 | 105.65 | 106 | 57.26 | 57 | 16 | 24 | 12,084 | 448 | 997 | 671 |
| 66 | 21.04 | 23.75 | 499.66 | 116.21 | 116 | 62.98 | 63 | 18 | 27 | 16,443 | 609 | 1357 | 812 |
| 72 | 21.98 | 28.26 | 621.08 | 126.78 | 127 | 68.71 | 69 | 20 | 29 | 21,177 | 784 | 1747 | 974 |

OUTLET PROTECTION
ROCK RIPRAP APRON

| PIPE DIAMETER | APRON DIMENSIONS LENGTH | WIDTH | ROCK SIZE | ROCK DEPTH | APRON QUANTITIES VOLUME | VOLUME | WEIGHT (165 lb/cf) | FILTER FABRIC AREA |
|---|---|---|---|---|---|---|---|---|
| Do (in) | $L_{sp}$ (ft) | $W_{sp}$ (ft) | $d_{50}$ (inches) | $D_a$ (inches) | V (cf) | V (cy) | V (tons) | A (sy) |
| 12 | 21 | 18 | 4 | 6 | 189 | 7 | 16 | 42 |
| 18 | 32 | 24 | 5 | 8 | 512 | 19 | 42 | 85 |
| 24 | 42 | 29 | 7 | 11 | 1,117 | 41 | 92 | 135 |
| 30 | 53 | 35 | 9 | 13 | 2,010 | 74 | 166 | 206 |
| 36 | 64 | 40 | 11 | 16 | 3,413 | 126 | 282 | 284 |
| 42 | 74 | 46 | 12 | 19 | 5,390 | 200 | 445 | 378 |
| 48 | 85 | 51 | 14 | 21 | 7,586 | 281 | 626 | 482 |
| 54 | 95 | 57 | 16 | 24 | 10,830 | 401 | 893 | 602 |
| 60 | 106 | 62 | 18 | 26 | 14,239 | 527 | 1175 | 730 |
| 66 | 116 | 68 | 19 | 29 | 19,063 | 706 | 1573 | 876 |
| 72 | 127 | 73 | 21 | 32 | 24,723 | 916 | 2040 | 1030 |