CHAPTER twelve

Inspection, Maintenance and Rehabilitation

INSPECTION

With an aging infrastructure, and a vast number of pipes and culverts in the transportation system, deterioration is a growing problem for transportation agencies. The traveling public does not see most pipes and many are located on roads with high volumes of traffic and often under high embankments. Even with scheduled bridge inspections that include the larger drainage structures, the condition of these pipes often becomes noticeable only after a problem arises such as settlement of the road, pipe failure or flooding. Once a problem arises, the cost of replacement not only includes the direct construction costs but also significant indirect costs as a result of accidents, delays, detours, cleanup due to pollutants leaking into the groundwater etc.

Drainage systems should be inspected on a routine basis to ensure they are functioning properly. Depending on pipe size, flow area, risk associated with pipe location, Average Daily Traffic, detour length, previous inspection rating, etc., structures may need to be inspected annually or on a two, three or four-year cycle. Inspections should also always be conducted following a major storm. Systems that incorporate infiltration are most critical since poor maintenance practices can soon render them inefficient. An efficient pipe assessment and maintenance program will aid in reducing failures and in the cost-effective planning and prioritizing of future replacement, repair or rehabilitation of the drainage structures.

Thorough inspection of sewers, culverts and other soil-metal structures should be conducted using established guidelines under which all inspectors follow and record findings in the same manner. Inspection can be carried out visually and recorded on standard forms as well as with still photographs or videos. Current electronic technology enables the inspector to communicate directly with a central office using facsimile or video transmission. Inspection software has also been developed by various highway departments which provide a more consistent method of reporting. The date of installation, a description and configuration of the product, the date of subsequent inspections and maintenance, should be properly recorded. The FHWA Culvert Inspection Manual (1986), AASHTO Highway Drainage Guidelines, Volume XIV and NCHRP Synthesis 303 all provide guidelines for inventory, inspection and evaluation of existing culverts. The Transportation Research Record published a culvert ranking model based on economic factors in 1991. More recently, numerous researchers and highway departments have developed guidelines on culvert inspection, rating and management as well as culvert cleaning and repair practices (California, Kansas, Maine, Missouri, Montana, New Jersey, Ohio, Tennessee, and Utah).

Inspection requires both environmental and structural assessment. These are discussed in the following section.

Figure 12.1 Pipe inspection.

ENVIRONMENTAL ASSESSMENT

Environmental assessment includes the conditions of soil side corrosion, water side corrosion, water side abrasion and clogging. Soil side corrosion can be determined by coring the structure and evaluating the soil-side coupon. Inspection includes a visual examination for spalling, red rusting, pitting and perforating. The soil corrosivity, including pH and resistivity, is recorded along with moisture, soluble salts and oxygen content.

Water side corrosion is determined by a visual examination for spalling, red rusting, pitting and perforating. The water corrosivity including pH, resistivity and hardness is also recorded.

Water side abrasion is also determined visually along with an assessment of structure slope, flow velocity and upstream bed load of either rock or sand.

Clogging due to the accumulation of sediment or debris can be readily assessed visually and measured manually.

Other environmental factors that could influence the service life of the culvert should also be noted. These could include such factors as anticipated changes in the watershed upstream of the culvert, industrial effluents, stray electrical currents and possible effects of severe climates.

See Chapter 9, Durability, for guidelines on corrosiveness of soils and water, abrasion, and information on site testing equipment.

STRUCTURAL ASSESSMENT

Structural assessment includes shape monitoring and investigating for signs of joint separation, crimping of the pipe wall, excessive deformation, invert lifting, pipe end lifting and pipe end distortion. Additional structural assessment requirements for structural plate soil-steel structures include inspecting for bolt hole tears and structural distress at the longitudinal seams. The National Corrugated Steel Pipe Association (NCSPA) offers a rating methodology for structural evaluation of in-service corrugated steel structures. It is listed as NCSPA Design Data Sheet No. 19 and is available from the NCSPA or member companies.

Shape Monitoring

Traditional monitoring methods have usually consisted of a visual inspection with measurements being taken only if serious signs of distress are observed. Other than the span and rise, geometric measurements are normally limited to selected chord lengths and offsets at specified cross sections. These dimensions can be related to the curvature of a section. The performance of the structure is judged primarily on deformation stability. Excessive flattening of a section makes it susceptible to snap-through instability. The extent of flattening that a structure can tolerate is not easily defined. Arbitrary limits on the reduction in the mid-ordinate heights have been used to define the severity of the deformations and the remedial measures required. The changes are usually measured from the design shape, since the as-built dimensions are rarely measured. Being flexible, it is possible that the pipe was deformed from the design shape during construction, with little or no subsequent deformations. Only an ongoing monitoring of the structure can confirm that the deformations have stabilized.

In photogrammetric monitoring, an object is photographed using specialized equipment following set procedures, and measurements are obtained from the photographic images. These measurements and some externally supplied information are used to determine, either analogically or analytically, the location of reference points in the three-dimensional object space. Photogrammetry is particularly useful in monitoring large or difficult-to-access structures.

Crimping of Pipe Wall

Crimping can be regarded as a consequence of local buckling in which the metallic shell buckles into a large number of waves, each of relatively small length. It can occur in the compression zone of the wall section when the pipe wall undergoes large bending deformations. This kind of crimping usually takes place in pipe wall segments of relatively small radius. It indicates that the soil behind the segment is not dense enough to prevent excessive bending deformations.

Crimping can also occur in an entire pipe wall section subjected to excessive thrust while being supported by very well compacted backfill. Although the incidence of this kind of crimping is rare, it is known to have occurred in structures with circular pipe, which were constructed with good-quality, well-compacted backfill on a relatively yielding foundation. It is assumed that the long-term foundation settlements of these structures induced negative arching, thus subjecting the pipe wall to greater and greater thrusts as time passed, until the thrust exceeded the buckling capacity of the pipe wall even though it was well supported horizontally.

Buckling of the entire pipe wall section into waves of small length has a redeeming feature. By reducing the axial rigidity and increasing axial deformations of the pipe, it induces positive arching, thus effectively reducing the axial thrust in the pipe. The result of this sequence is that, despite crimping, the pipe can be in a stable condition provided, of course, that the time-dependent foundation settlements have ceased.

If the only sign of distress in a soil-steel structure is crimping limited to a few segments, then in most cases one need not be too concerned about the structural integrity.

Excessive Deformation

Excessive deformations of the pipe wall are caused by the inability of the backfill to restrain its movement. Because of its flexibility, the pipe can deform excessively during the initial stages of the backfilling operation. If such deformation is not prevented or corrected during construction, the structure is built with deformed pipe. Pipe deformations locked in during construction may not be detrimental to the structural integrity of the structure, especially if they have stabilized. Pipe deformation occurring after the completion of the structure may, on the other hand, be a warning signal for the imminent collapse of the structure.

It is very important that a record of the as-built pipe shape be kept so that it can be ascertained later whether the observed deformation occurred recently or has been there since the construction of the structure. When the records of the as-built structure are not available, it is important to record the changes in the pipe shape at regular intervals after the deformations were first noticed. If the deformations are not significant and have not undergone significant changes, then it is likely that the structure will perform as intended.

Lifting of Invert

In soil-steel structures with a large radius or flat invert plates, the pressure under the corners is much greater than under the invert plates. If the foundation has inadequate bearing capacity the structure settles more under the haunches than under the invert. This results in a loss of waterway area and may deteriorate the structural capacity of the structure.

Lifting of Pipe Ends

This is another form of distress sometimes found in hydraulic structures. This kind of distress is caused by a combination of uneven settlement of the pipe foundation along its length, buoyancy effects and CSP joints located too close to the end of the pipe.

Distortion of Beveled Ends

Beveled ends are particularly vulnerable to damage by horizontal pressures. A complete pipe provides a closed section and thus, can sustain much higher intensities of lateral pressure than an incomplete ring. Lacking a closed section, the beveled ends of a pipe are prone to damage by lateral earth pressures or from vehicle impact or heavy equipment pieces falling on them. To resist this, beveled ends can be reinforced or tied back to deadman anchors in the fill.

Joint Separation

CSP offers some of the structurally strongest joints available, yet separation of the joints may occur due to uneven settlement along the pipe, steep slopes, improper bedding, backfill or alignment during construction or movements due to earthquakes or frost.

Bolt-hole Tears in Structural Plate Structures

Bolt-hole tears or cracks may occur in longitudinal seams. Since the pipe wall is always subjected to compressive forces, the bolt-hole tears usually do not extend over the entire section of the wall.

Bolt-hole tears are most common in pipe arches at the longitudinal seam between the top and side segments of the wall. This location predominates because excessive shape changes induce excessive bending and bolt tension at the inside valley bolt holes. However, they are also found, very infrequently, in other soil-steel structures. Bolt-hole tears are not always the result of excessive deformation of the pipe wall of the completed structure; they can also be formed during assembly when poorly matching plates are forced to fit at the longitudinal seams.

Reviews of this issue have been conducted and all reports conclude that there is a correct and incorrect way of lapping the plates at longitudinal seams.

The correct orientation for longitudinal seam plate lap results in the valley bolt being located closest to the visible plate edge. This is illustrated in Figure 12.2.

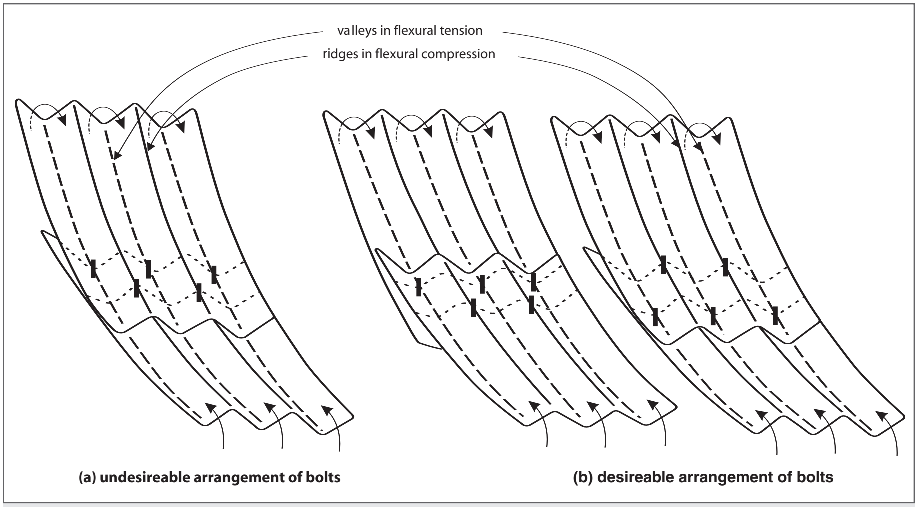


Figure 12.2 (a) Undesirable and (b) desirable arrangement of bolts. (Reproduced from Canadian Journal of Civil Engineering, Volume 15, Number 4, 1988, Pages 587 - 595: Bakht and Agarwal)

Distress at Longitudinal Seams in Structural Plate Structures

Distress at longitudinal seams can be observed as a result of yielding of the wall directly under the bolts or shear failure of the bolts. Such distress occurs under excessive pipe wall thrust and under conditions that preclude excessive bending deformations.

While failure of longitudinal seams has been observed in laboratory testing to determine strength of bolted joints, it is extremely rare to find in practice.

MAINTENANCE

Procedures and equipment for maintenance of drainage systems are discussed in this section. As with inspection, good records should be kept on all maintenance operations to help plan future work and identify facilities requiring attention. Various types of equipment are available commercially for maintenance of drainage systems. The mobility of such equipment varies with the particular application and the equipment versatility.

Trenches

The clogging mechanism of trenches is similar to that associated with other infiltration systems. Although the clogging of trenches due to silt and suspended material is more critical than that of basins, it is less critical than the clogging of vertical wells. The use of perforated pipe will minimize clogging by providing catchment for sediment without reducing overall efficiency. Maintenance methods associated with these systems are discussed later in this chapter.

Catch Basins

Catch basins should be inspected after major storms and cleaned as often as needed. Various techniques and equipment are available for maintenance of catch basins as discussed in the next section. Filter bags can be used at street grade to reduce the frequency for cleaning catch basins and outflow lines.

Vacuum Pump

This device is normally used to remove sediment from sumps and pipes and is generally mounted on a vehicle. It usually requires a 200 to 300 gal. holding tank and a vacuum pump that has a 10 inch diameter flexible hose with a serrated metal end for breaking up caked sediment. A two-man crew can clean a catch basin in 5 to 10 minutes. This system can remove stones bricks, leaves, litter, and sediment deposits. Normal working depth is 0 to 20 feet.

Waterjet Spray

This equipment is generally mounted on a self-contained vehicle with a high pressure pump and a 200 to 300 gal. water supply. A three inch diameter flexible hose line with a metal nozzle that directs jets of water out in front is used to loosen debris in pipes or trenches. The nozzle can also emit umbrella-like jets of water at a reverse angle, which propels the nozzle forward as well as blasting debris backwards toward the catch basin. As the hose line is reeled in, the jetting action forces all debris to the catch basin where it is removed by the vacuum pump equipment. The normal length of hose is approximately 200 feet. Because of the energy supplied from the waterjet, this method should not be used to clean trench walls that are subject to erosion.

Bucket Line

Bucket lines are used to remove sediment and debris from large pipes or trenches (over 48 inch diameter or width). This equipment is the most commonly available type. The machine employs a gasoline engine driven winch drum, capable of holding 1000 feet of $^1/_2$ inch diameter wire cable. A clutch and transmission assembly permits the drum to revolve in a forward or reverse direction, or to run free. The bucket is elongated, with a clam shell type bottom that opens to allow the material to be dumped after removal.

Buckets of various sizes are available. The machines are trailer-mounted usually with three wheels, and are moved in tandem from site to site. When a length of pipe or trench is to be cleaned, two machines are used. The machines are set up over adjacent manholes. The bucket is secured to the cable from each machine and is pulled back and forth through the section until the system is clean. Generally, the bucket travels in the direction of the flow and every time the bucket comes to the downstream manhole, it is brought to the surface and emptied.

Fire Hose Flushing

This equipment consists of various fittings that can be placed on the end of a fire hose such as rotating nozzles, rotating cutters, etc. When this equipment is dragged through a pipe, it can be effective in removing light material from walls. Water can be supplied from either a hydrant or a truck.

Sewer Jet Flushers

The machine is typically truck-mounted and consists of a large water tank of at least 1000 gal., a triple action water pump capable of producing 1000 psi or more pressure, a gasoline motor to run the pump, a hose reel large enough for 500 feet of 1 inch inside diameter high pressure hose and a hydraulic pump to remove the loose material. In order to clean pipes properly, a minimum nozzle pressure of 600 psi is usually required. All material is flushed ahead of the nozzle by spray action. This extremely mobile machine can be used for cleaning areas with light grease problems, sand and gravel infiltration, and for general cleaning.

REHABILITATION

Rehabilitation of the infrastructure is a major undertaking now being addressed by federal, state, and local governments. While the magnitude of rehabilitation may at times appear enormous, rehabilitation often is very cost-effective when compared to the alternative of new construction.

This section deals primarily with the use of CSP, corrugated structural plate, or steel tunnel liner plates to cost-effectively restore the structural capacity of deteriorated or failing culvert and bridge structures. These deteriorated structures include precast or cast-in-place concrete structures, concrete, steel or plastic pipe and all types of existing bridge structures. The corrugated steel material is typically inserted or assembled inside the failing structure and the annular space between the liner and deteriorated structure is filled with grout. This rehabilitation technique is commonly referred to as slip lining. After the grout has set, the repaired structure usually becomes much stronger than the original one and remains virtually free of distress.

Deteriorated CSP structures can often be rehabilitated by merely providing a new wear surface in the invert. If necessary they can also be repaired by slip lining or by a number of other methods to provide a new, complete service life at a fraction of the cost or inconvenience of replacement. A practice for placing a concrete invert or entire lining is provided in ASTM specification A 979/A 979M. Some of these repair and rehabilitation methods are also described in this section.

All of the methods described herein require a complete inspection and evaluation of the existing pipe to determine the best choice of corrugated steel material and coatings.

Rehabilitation by Slip Lining

Materials and Details for Slip Lining

Use of CSP or structural plate products has a number of advantages for sliplining applications. Standard corrugated steel pipe, manufactured in accordance with AASHTO M 36 or ASTM A 760/A 760M, may be provided in any lengths which would facilitate insertion at the site. The CSP liner pipe can be manufactured to any standard size or virtually any custom size, round or arched in shape, to fit the existing pipe cross-section. Accurate surveying of the existing structure is important to determine the maximum size of liner pipe that can be installed. A hydraulic advantage may be gained by using helical corrugated steel pipe if the existing pipe is annular corrugated or hydraulically rough due to excessive deformations. If the owner desires to maintain maximum hydraulic capacity of the line, then the use of a smooth lined corrugated steel pipe is recommended. Choices of this type of pipe include ribbed pipe, double wall CSP, 100% cement mortar lined, and 100% asphalt lined. A number of coatings are also available to provide the required remaining design life for the structure (see Durability Chapter 9).

Figure 12.3 Typical slip lining installation with a pipe arch shape to suit existing cross-section.

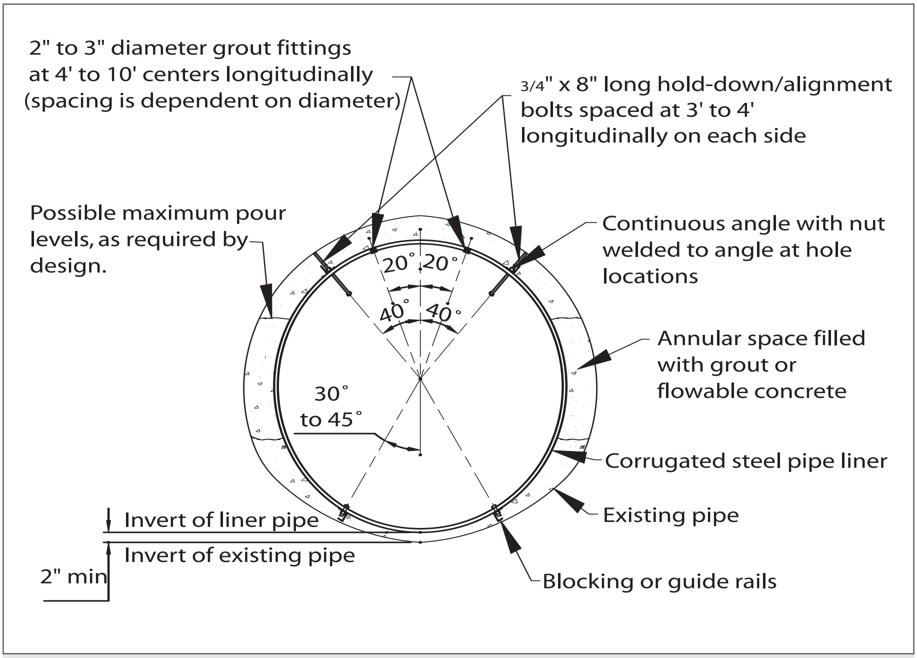
CSP is lightweight, making it easy to handle and install. Skid devices may consist of steel or pressure treated wood guide rails placed on the invert of the existing pipe, or skid bars attached to the liner pipe to facilitate moving it in to the desired location. These devices also maintain a minimum space between the bottom of the liner and the existing structure to facilitate proper grouting. Adjusting bolts are used to secure the slipline pipe in position and prevent floating of the pipe during grouting. These usually consist of 3/4 inch diameter rods, threaded through nuts or steel angles welded to the outside of the liner plate. Typical spacing is approximately 5 to 10 foot centers and at about 40 degrees on each side of the top centerline. For relining a concrete box shape, three sets of these rods would be used, located at the top and spring line on each side of the liner pipe. Grout fittings are welded to the liner pipe wall at positions and spacing as determined by the Engineer. See Figures 12.8 and 12.9 for typical details of slip line installations.

■ **Figure 12.4** Pipe sections can be fabricated in lengths as required to suit slip lining installation.

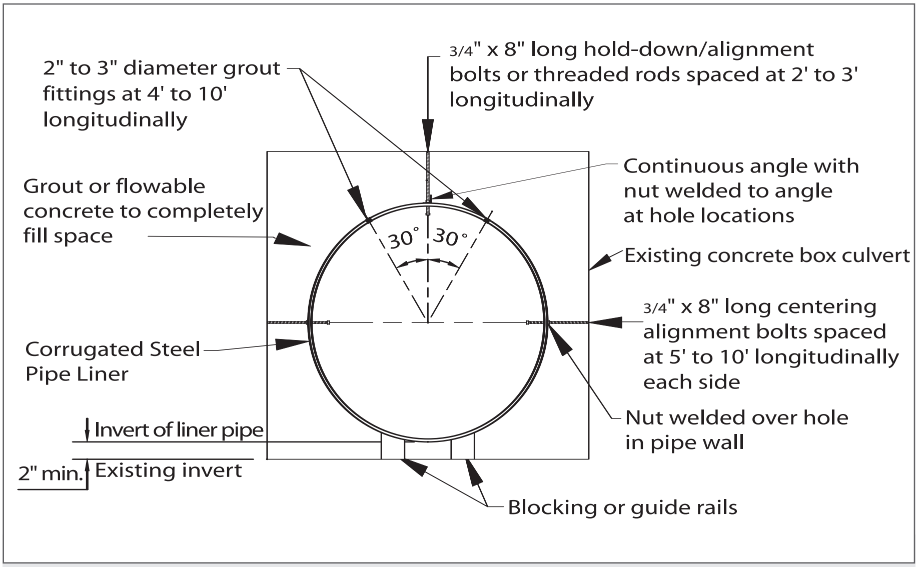
■ **Figure 12.5** Liner pipe is easily installed by pushing or pulling through host pipe using conventional equipment.

■ **Figure 12.6** Liner pipe being installed in an existing concrete box.

■ **Figure 12.7** Deep corrugated box culvert lining a falling bridge. Note the dozer pulling the corrugated box culvert into position.



■ **Figure 12.8** A typical section of a corrugated steel pipe slip line installation in a round pipe.



■ **Figure 12.9** A typical section of a corrugated steel pipe slip line installation in a concrete box culvert.

Various types of connecting bands and gaskets are available to suit site requirements. If sufficient clearance exists between the liner pipe and the existing line, the sections may be joined by the use of a threaded rod and lug type coupling band as shown in Figure 12.10. Internal expanding coupler bands as shown in Figure 12.11 are recommended if there is insufficient clearance on the outside of the liner pipe. Another alternative is to use sheet metal screws or Huck© rivets in conjunction with an installation jig.

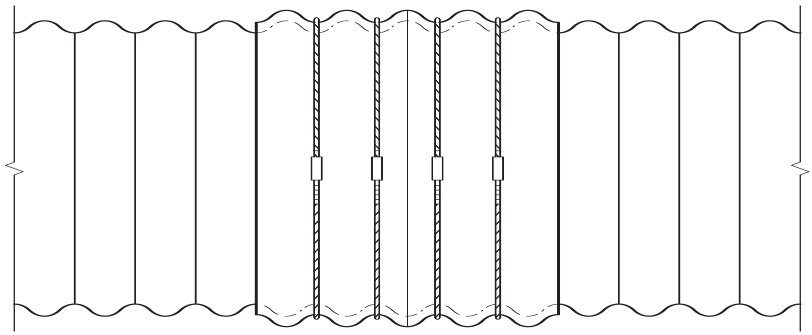


Figure 12.10 Band is secured by rods around band connected by lugs.

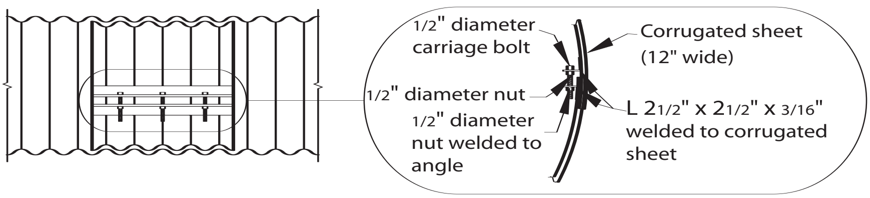


Figure 12.11 The use of an internal expanding type coupling band is recommended to connect the section if there is insufficient clearance on the outside of the liner pipe.

For large deteriorated structures and bridges, corrugated structural plate or tunnel liner plate can be used as the liner, either assembled in-place or outside the structure and slid into place as with CSP. Structural plate can be manufactured in a variety of shapes to suit the project including round, pipe arch, arch, box shape and elliptical. Deep and shallow corrugated plate is available, dependent on the design requirements. It is important to work with the pipe manufacturer and the contractor to determine the material and details for connection and installation to best suit the project.

■ **Figure 12.12** Lining a concrete box with a steel box culvert.

Grouting of Slip Lined Pipe

Bulkheads must be placed at each end of the installation or at staged intervals for longer projects. Grouting of the annular space is usually accomplished using a sand-cement grout mixture, progressively pumped at low pressure along the length of the pipe using spaced grout fittings starting at the low end. Depending on the length of the liner, the grout can sometimes be pumped through an opening in the end bulkheads. The grout pressure and flow rate must be carefully controlled to prevent failure of the liner pipe and excessive flotation forces. The grout is placed in lifts to limit flotation and buckling pressures. It is important to follow a progressive grouting procedure, utilizing inspection ports, to completely fill the annual space. In some installations the grout is placed through an opening at the roadway surface above the liner pipe.

The grout material should be a non-shrink mix with a minimum 28-day compressive strength of 300 psi. Non-corrosive fly ash and non-chloride admixtures are generally permitted in the grout mix. A typical grout mixture could consist of one part of cement and five parts fine aggregate, by volume, with 10 pounds of fly ash added for each bag of cement. If internal coupling bands are used they can be removed after the grout has achieved initial set.

■ **Figure 12.13** Structural plate arch with grout plugs used to line concrete box culvert.

■ **Figure 12.14** Grout can be pumped into annular space through an opening in the end bulkheads.

■ **Figure 12.15** Finished end treatment.

Design of Slip Line Pipe

The liner pipe is typically designed as a conventional flexible structure to carry all the imposed dead and live loads. However, if grouting is controlled or appropriate blocking techniques are used, the flexibility requirements can be relaxed. The existing structure, which will remain in place and continue to support all or a portion of the loads on it, and the contribution of the surrounding grout are generally totally ignored. A new analysis method for the complex soil-structure interaction of the grouted system has not yet been developed and verified. The liner installation must also be checked for buckling due to anticipated hydrostatic or grout pressures and flotation forces for the installation.

Rehabilitation of CSP and Structural Plate Pipes

Although a pipe may be deemed structurally deficient, this does not rule out rehabilitation. In fact, an existing structure that has not failed still has a factor of safety of 1.0 or more. Repair methods can be utilized and the structure restored to structural adequacy and then normal rehabilitation procedures performed. Even with 25% metal loss, which occurs long after first perforation, structural factors of safety are reduced by only 25%. When originally built, CSP designs often provide factors of safety of 4 to 8—far in excess of that required for prudent design. This section deals mainly with the rehabilitation or repair of corrugated steel pipe and/or steel structural plate.

There are two categories of pipe rehabilitation, invert rehabilitation and total pipe rehabilitation.

Invert Rehabilitation

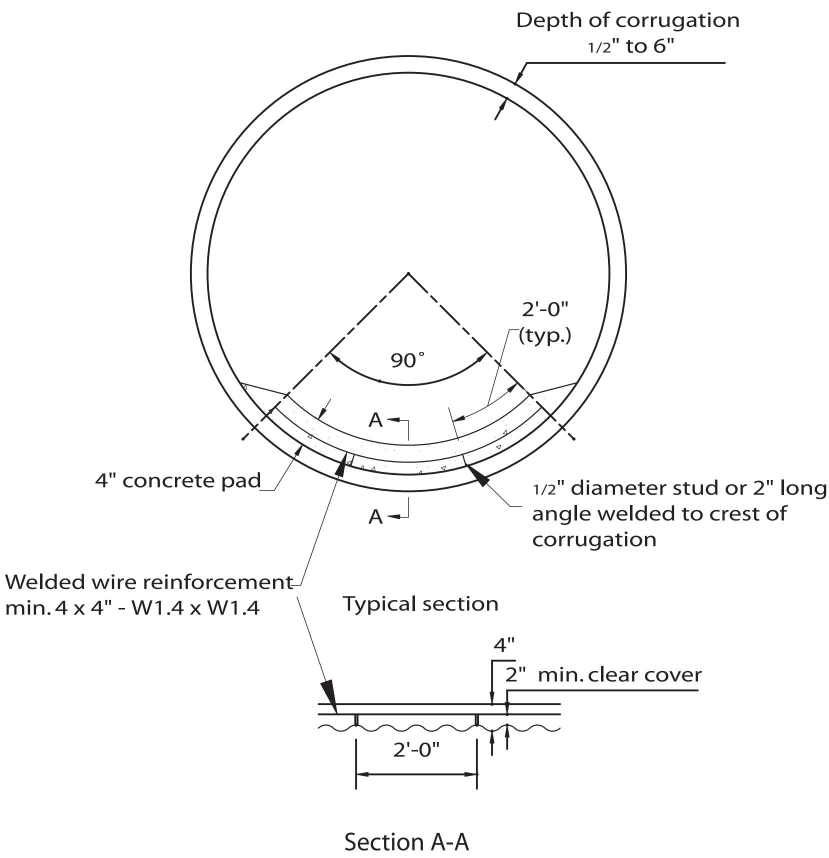
The inverts of CSP and structural plate pipes usually deteriorate faster than the rest of the culvert. When deterioration is limited to the invert, the pipe can be rehabilitated by replating the invert with new corrugated steel plates or by attaching heavy gage flat steel armor plates to the sides and bottom of the invert, Figure 12.16. For larger diameters where it is possible for a person to enter the pipe, a new concrete invert, or pavement, may be cast in the pipe. Plain troweled concrete may be satisfactory for mild conditions of abrasion and flow. For more severe conditions a reinforced concrete pavement is required. Figure 12.17 shows typical reinforcing and configuration of field placed concrete pavement. The final design should be in the control of the Engineer and depends upon the extent of the deterioration of the pipe. Additional details and specifications are provided in ASTM specification A 979/A979M.

Figure 12.16 Steel armor-plated invert.

Total Pipe Rehabilitation Using Relining Materials

The selection of the reline material is dependent upon the conditions of the pipe line to be rehabilitated and the diameter and/or shape. If the line has deteriorated to the point where it is deficient structurally, the choice would necessarily have to be a material having full barrel cross section with sufficient structural capability to withstand the imposed dead and live loads.

The following is a discussion of reline materials and methods of installing them. It is the Engineer's responsibility to select the material and method of relining dependent upon rehabilitation requirements. Alternate types of materials may be found in ASTM A 849.



■ **Figure 12.17** In-place installation of concrete invert.

Slip Lining

Slip lining a deteriorated pipe using CSP is usually the most cost-effective means of restoring the full structural capacity of the pipe where some downsizing of the line is not a concern. Often the original pipes are oversized to allow for future sliplining with a size meeting the hydraulic requirements. Inlet improvements may also compensate for the reduced flow area. The materials, procedures and details for slip lining CSP are as described previously for rehabilitating other types of deficient structures.

■ **Figure 12.18** Concrete paved invert in structural plate pipe.

■ **Figure 12.19** Slip lining with CSP.

Inversion Lining

Inversion lining is accomplished by using needle felt, of polyester fiber, which serves as the "form" for the liner. The liner expands to fit the existing pipe geometry and therefore is applicable to round, elliptical pipe and pipe arch. The use of this method requires that the pipe be taken out of service during the rehabilitation period. One side of the felt is coated with a polyurethane membrane and the other is impregnated with a thermosetting resin.

The felt variables include denier, density, type of material, method of manufacture (straight or cross lap), and length of fiber. The physical properties of the felt and chemicals must be determined for the specific project and in cooperation with prospective contractors.

Inversion lining has been utilized on lines from 4 to 108 inches in diameter. It is normally applicable for distances of less than 200 feet or where ground water, soil condition, and existing structures make open excavation hazardous or extremely costly. Inversion lining with water is generally confined to pipelines with diameters less than 60 inches and distances less than 1000 feet. Normally air pressure is utilized for inversion technique on larger diameter pipe. Compared with other methods, this process is highly technical. Other technical aspects include resin requirements which vary with viscosity, felt liner, ambient temperatures, and the filler in the felt content; the effects of ultraviolet light on the resin and catalyst; and safety precautions for personnel and property.

Shotcrete Lining

Shotcrete is a term used to designate pneumatically applied cement plaster or concrete. A gun operated by compressed air is used to apply the cement mixture. The water is added to the dry materials as it passes through the nozzle of the gun. The quantity of water is controlled within certain limits by a valve at the nozzle. Low water ratios are required under ordinary conditions. The cement and aggregate is machine or hand mixed and is then passed through a sieve to remove lumps too large for the gun.

When properly made and applied, shotcrete is extremely strong, dense concrete, and resistant to weathering and chemical attack. Compared with hand placed mortar, shotcrete of equivalent aggregate-cement proportions usually is stronger because it permits placement with lower water-to-cement ratios. For relining existing structures, the shotcrete should be from 2 to 4 inches thick depending on conditions and may not need to be steel reinforced. If used, the cross-sectional area of reinforcement should be at least 0.4% of the area of the lining in each direction.

Shotcreting with a steel-fiber-reinforced concrete mix has been used successfully to line the inside of soil-steel bridges in distress. The lining, which is up to 6 inches thick, may cover the complete perimeter of the cross section of the pipe. Alternatively, it may be limited to the damaged zone of the pipe wall.

When shotcreting is used for the complete ring, shear connectors are not usually provided between the pipe wall and the shotcrete. However, their inclusion can certainly increase the strength and stiffness of the additional ring.

The partial shotcrete ring is provided to repair localized damage, such as a section containing bolt-hole tears. For the partial ring, it is important to provide a shear connection between the pipe and shotcrete. This shear connection may be by shear studs of the type used in composite beams, or machine-welded to the pipe after the zinc coating from the galvanized plate has been ground off locally. An alternative to the usual shear stud is a U-shaped bracket of 12 gage galvanized steel sheet, which is attached to the pipe through pins, fired by a ram-setting gun. This type of shear connector, which is shown in Figure 12.20, has been used successfully in several cases.

Despite the ability of the fiber-reinforced concrete to sustain fairly large tensile stresses, it is advisable to add a steel reinforcement mesh to the shotcrete ring, especially if it is partial. Repair by fiber-reinforced shotcrete can prove economical and effective in many cases, mainly because of the fact that it requires no formwork and little preparatory work. Because of its relatively thin layer, the shotcrete ring does not reduce the pipe size appreciably. The repair work by shotcreting can be undertaken even in cold weather, provided that the pipe wall sections to be shotcreted are adequately heated. If only the top and side segments are to be repaired, then shotcreting of culverts can be carried out without diverting the stream.

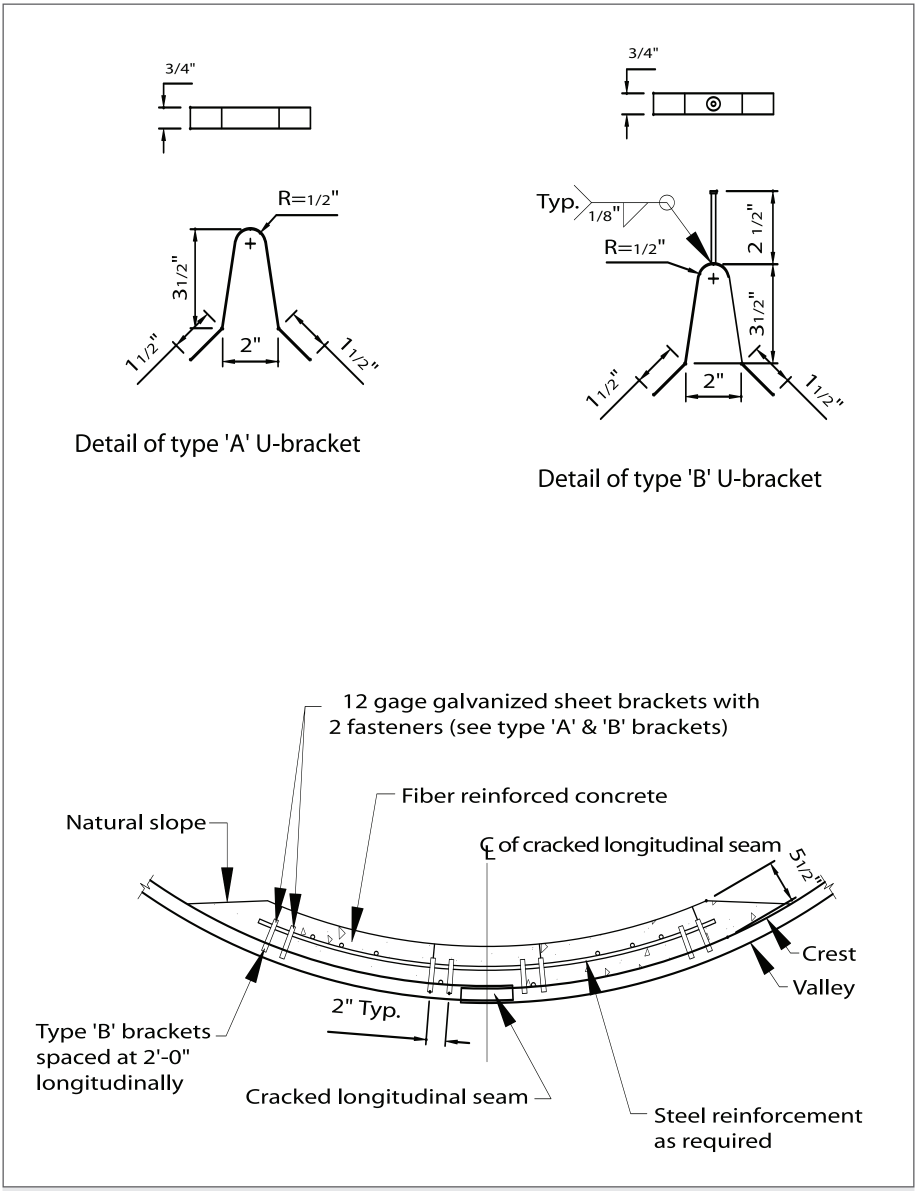
The following specifications should be considered:

1. "Specifications for Concrete Aggregates", ASTM C 33.
2. "Specifications for Materials, Proportioning and Application of Shotcrete", ACI 506.
3. "Specifications for Chemical Admixtures for Concrete", ASTM C 494.

Cement Mortar Lining

Cement mortar lining is particularly well suited to small diameter pipe that is not easily accessible.

The cement mortar lining is applied in such a manner as to obtain a 1/2 inch minimum thickness over the top of the corrugations. Application operations should be performed in an uninterrupted manner. The most common practice uses a centrifugal machine capable of projecting the mortar against the wall of the pipe without rebound, but with sufficient velocity to cause the mortar to be densely packed in-place. See Figure 12.21, which shows a typical setup for this process.



■ **Figure 12.20** Partial shotcrete ring.

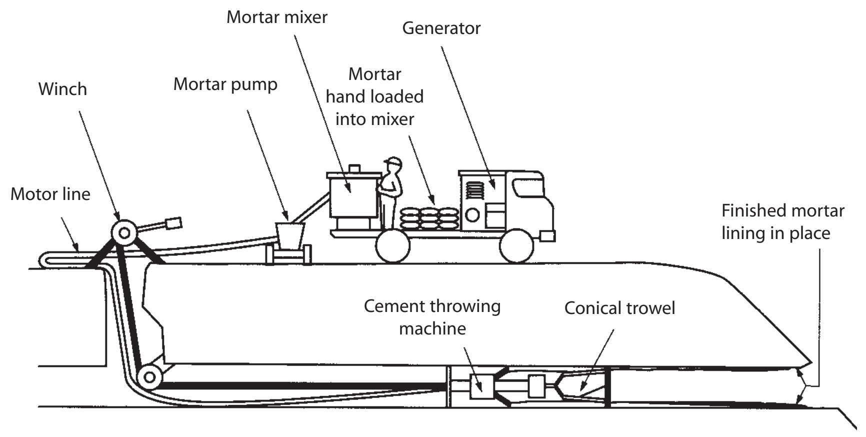


Figure 12.21 Cement mortar lining.

Other Repair and Rehabilitation Techniques and Considerations

Temporary Props

One of the most effective and expedient measures to ensure that excessive deformations of the pipe do not degenerate into sudden collapse is the provision of temporary struts or props in the pipe. These props can be timber columns of about 8 inches x 8 inches cross section, or steel struts of hollow circular section of the kind used in construction formwork. The props are located in the pipe under the crown and are provided with longitudinal sills above and under them. The sills, which run along the pipe length, are typically timber. When the sides of the pipe cross section are also excessively flattened, the vertical props are supplemented with horizontal supports.

The main advantage of vertical props is that they can prevent a catastrophic failure of the structure; the main disadvantage is that they constrict water flow. This disadvantage can be particularly significant for culverts. The props should be designed to carry, with an adequate margin of safety, the weight of that volume of soil apportioned to them. The props are usually spaced at 3 to 5 feet. The butt joints of the top and bottom sills should be staggered so that they do not occur at the same location along the pipe. The sills should be long enough to contain at least two props. Screws for adjusting the lengths of these props are very effective in ensuring that the contact between the supports and the pipe is not loose. Hydraulically, actions need to be taken to ensure debris does not collect on the structural system and clog the pipe.

Patching

Numerous patching compounds are commercially available. Compounds such as epoxies, which are used in bridge and paving repair can be used. Low shrink grout, plain and reinforced concrete, and polymerized asphalt are candidate materials that can be used to plug leaks, holes or restore inverts. A number of the above procedures are applicable to both concrete and steel pipe. However, use of welding and mechanical fasteners for repair is applicable only to steel pipe. Thus, the ease of maintenance associated with steel is a major factor in economical culvert and storm sewer design.

Partial Concreting Outside The Pipe

When distress in the pipe wall is limited to only the top segments of the pipe and the depth of cover is shallow, removal of the backfill from above the pipe and adding a layer of concrete to the outside of the pipe may prove to be an economically viable repair method. In this method, the concrete layer may be made composite with the pipe through the usual shear studs employed in slab-on-girder-type bridges. Where needed, shear studs can be machine-welded readily to the pipe after locally grinding off the zinc layer. The shear studs are staggered for maximum efficiency.

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GLOSSARY

Definition of Terms:

Many terms in this handbook are common to drainage, highway, and other related design and construction disciplines. Most of these are defined, described or illustrated where they appear in the book. However, to aid the engineering student and to clear up unfamiliar words for the professional engineer, a number of terms are here defined even though they may be elementary. For other unfamiliar terms, many are keyed in the index of this book, particularly where the definitions already appear in the text.

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A

abrasion—Wear by hydraulic traffic.

abutment—A wall supporting the end of a bridge or span, and sustaining the pressure of the abutting earth.

aerial sewer—An unburied sewer (generally sanitary type) supported on pedestals or bents to provide a suitable grade line.

aggradation—Progressive raising of the general level of a channel bed over a period of years by an accumulation of sediment.

allowable headwater elevation—The maximum permissible elevation of the headwater at a culvert at the design discharge.

allowable headwater depth—The depth corresponding to the allowable headwater elevation, measured from the invert at the first full cross section of the culvert.

allowable fish passage velocity— The maximum velocity fish can tolerate when passing upstream through a culvert.

anchor bolt—A foundation bolt; a drift spike, or any other device used for holding any mechanism or structure down. It may or may not be threaded.

angle—A rolled piece of steel having a cross section shaped into a right angle.

angle of repose—The angle which the sloping face of a bank of loose earth, or gravel, or other material makes with the horizontal.

anti-seep collar—see diaphragm

apron—Protective material laid on a stream bed to prevent scour at a culvert outlet, abutment, pier, toe of a slope, or similar location. (see also end section)

arch—Structural plate corrugated steel pipe formed to an arch shape and placed on abutments. The invert may be the natural stream bed or any other suitable material but is not integral with the steel arch.

arching—The effect produced by transfer of pressure between adjoining soil masses which settle relative to each other. Positive or active arching is that which results in the transfer of loads away from the conduit; negative or passive arching produces the opposite effect.

armor stone—A layer of stone protecting erodible material underlying the bed of a channel.

asphalt coating—Dipping corrugated steel pipe products, in a bath of hot asphalt for protection.

B

backfill—Earth or other material used to replace material removed during construction, such as in culvert, sewer and pipeline trenches and behind bridge abutments and retaining walls. Also refers to material placed in binwalls or between an old structure and a new lining.

backfill density—Percent compaction for pipe backfill (required or expected).

backwater—The rise of water level upstream due to an obstruction or construction in the channel.

backwater curve—Term applied to the calculation of the piezometric line from the obstruction.

baffle —A flow interference structure usually in the form of a low weir, which is attached to a culvert invert and extends partially or entirely across the culvert width. Baffle designs are constructed to aid in fish passage through the culvert barrel, or the channel.

band coupling—A collar or coupling which fits over adjacent ends of pipe to be joined, which when drawn tight, holds the pipe together by friction or by mechanical means. Types commonly available include: universal, corrugated. semi-corrugated, channel, flat, wing channel and internal expanding.

base (course)—A layer of specified or selected material of planned thickness, constructed on the sub-grade (natural foundation) or sub-base for the purpose of distributing load, providing drainage, or upon which a wearing surface or a drainage structure is placed.

batter—The slope of inclination from a vertical plane - as the face or back of a wall.

bedding—The earth or other material on which a pipe or conduit is supported.

bed load—Sediment in the flow that moves by rolling, sliding, or skipping along the bed; and is essentially in contact with the stream bed.

bend section—Intersection of the fall slope and barrel slope in a slope-tapered inlet.

bent protection system—Casing of structural plate or corrugated steel pipe installed to protect pile or framed bents.

berm—The space between the toe of a slope and excavation made for intercepting ditches or borrow pits.

- An approximately horizontal space introduced in a slope.
- Often used for word "shoulder" in road work.

beveled end—A cut-end treatment for structural plate products. The cut is on a plane inclined to the horizontal.

beveled inlet—A large chamfer or flare on the inlet edge of a culvert to improve the inlet coefficient Ke. Usually cast-in-place.

binwall—A series of connected bins, generally filled with earth or gravel to serve as a retaining wall, abutment, pier, or as protection against explosions or gunfire. (See Chapter 11)

bituminous (coating)—Of or containing bitumen; as asphalt or tar.

blue-green concept—The provision of stormwater detention ponds or lakes as an integral part of a park or greenbelt. In urban design, culvert sizing at roadways may be used to create temporary storage in the channel.

boring—An earth-drilling process used for installing conduits or pipelines.

box beam—Steel guardrail consisting of box sections cold formed from steel tubes.

box culvert—Drainage structure fabricated with standard structural plate reinforced with circumferential ribs having straight side legs bolted to corner plates curved to a small radius and a crown of large radius plates.

bridge plank (deck flooring)—A corrugated steel sub-floor on a bridge to support a wearing surface.

buoyancy—The power of supporting a floating body, including the tendency to float an empty pipe (by exterior hydraulic pressure).

burst speed—The swimming speed a fish can maintain for only a few seconds or for short distances without gross reduction of performance.

C

caisson—A watertight box or cylinder used in excavating for foundations or tunnel pits—to hold out water so concreting or other construction can be carried on.

camber—Rise or crown of the center of a bridge, or Bowline through a culvert above a straight line through its ends. A measure of adjustment required in the longitudinal profile of the bedding, in order to compensate for post-construction settlement. See Index.

cantilever—The part of a structure that extends beyond its support.

catch basin—A receptacle for diverting surface water to a sewer or subdrain, having at its base a sediment bowl to prevent the admission of grit and other coarse material into a sewer.

cathodic protection—Preventing corrosion of a pipeline by using special cathodes (and anodes) to circumvent corrosive damage by electric current.

- Also a function of zinc coatings on iron and steel drainage products—galvanic action.

channel treatment—Refers to the design to improve flow, or to reduce scour and/or erosion in the channel above or below the culvert. This, may include debris barriers before the inlet; paving or rip-rap to accelerate or decelerate flow velocity; training walls to direct flow; channel linings such as gabions, gobimats, special grasses, etc.; special inlet designs to improve or upgrade culvert capacity; special outlet designs for velocity scour prevention and/or energy dissipation; tailpond level control weirs for fish passage; and fish ladders above or below the culvert, or inside the culvert barrel.

chute—A steeply inclined channel for conveying water from a higher to a lower level.

closed invert culvert—A culvert having an invert which is structurally integral with the walls.

coefficient of runoff—Percentage of gross rainfall which appears as runoff. Also ratio of runoff to depth of rainfall.

cofferdam—A barrier built in the water so as to form an enclosure from which the water is pumped to permit free access to the area within.

cohesive soil—A soil that when unconfined has considerable strength when air-dried, and that has significant cohesion when submerged.

collar—An end treatment for a culvert, usually consisting of a concrete ring surrounding a cut-end treatment. The collar is usually attached to a cutoff wall.

combined sewer—A sewer that carries both storm water and sanitary or industrial wastes.

compaction—The densification of a soil by means of mechanical manipulation.

competent velocity—The velocity of water which can just move a specified type or size of material on a streambed.

conduit—A pipe or other opening, buried or above ground, for conveying hydraulic traffic, pipelines, cables or other utilities.

consolidation—The gradual reduction in a volume of a soil mass resulting from an increase in compressive stress.

conventional culvert—A closed invert culvert having no major inlet improvements such as a side-tapered or slope-tapered inlet. It may incorporate minor improvements such as, cut-end treatments, beveled edges, wingwalls, a fall, or a prefabricated end section.

conveyor conduit—Corrugated steel structures of varying diameters used to enclose a conveyor system.

conveyor cover—Half circle steel arch sections supported on bandsheets which are bolted to the conveyor frame.

conveyor tunnel—Usually a large diameter structural plate pipe installed to enclose a materials handling system. Commonly used under aggregate piles.

cooling water intake or discharge lines—A large diameter conduit carrying cooling water to a power plant and heated return water to the source. These lines are usually subaqueous requiring special underwater installation by divers.

corrugated steel pipe (CSP)—Galvanized sheet steel formed to finished shape by the fabricator:

- **riveted**—A corrugated steel pipe with annular corrugations, fabricated from cut-to-length corrugated steel pipe sheet with lapped longitudinal and circumferential seams fastened with rivets.
- **double wall**—A full circular cross section pipe helically formed with an outer corrugated shell and integrally seam-connected with an inner liner of smooth or uncorrugated steel sheet.
- **helical**—Corrugated steel pipe with helical corrugations, fabricated from coiled corrugated steel pipe sheet, with a continuous helical seam, either lock or welded.
- **spiral rib**—A full circular cross-section pipe with a single thickness of smooth sheet, fabricated with helical ribs projecting outwardly.

corrugated steel pipe sheet—A mill product in sheet or coil form for fabricating riveted or helical corrugated steel pipe products, galvanized by the continuous hot-dip process. (abbrev. "CSP sheet")

cost effective—Answering the purpose of providing the optimum effect at the most reasonable cost.

coupler—See band coupling.

critical density—Zone separating the levels of backfill compaction that will and will not prevent deflection failure of a pipe (Between 70% and 85% standard density).

critical depth—Depth of flow at which specific energy is a minimum for a given flow. Water depth in a conduit at which certain conditions of maximum flow will occur. Other conditions are: (1) the conduit is on a critical slope with water flowing at critical velocity, (2) there is an adequate supply of water.

critical flow—A condition that exists at the critical depth, and where the sum of the velocity head and static head is a minimum. Also, that flow which has a Froude number of one.

critical migration delay period—The maximum delay fish can tolerate during the spawning migration without harmful biological consequences.

critical slope—The slope at which a maximum flow will occur at minimum velocity. The slope or grade that is exactly equal to the loss of head per foot resulting from flow at a depth that will give uniform flow at critical depth.

critical velocity—Mean velocity of flow when flow is at critical depth.

crown—The highest point on a transverse section of conduit. (see soffit) Also the highest point of a roadway cross section.

culvert—A culvert is a conduit for conveying surface water through an embankment. It is a "grade separation" for water and the traffic or facility above it. The embankment may be for a highway, railway, street, industrial roadway, spoil bank, dam or levee.—A distinction is made between culverts and storm sewers, mostly on the basis of length and the types of inlets and outlets. Distinction is also made between culverts and bridges in that the top of a culvert does not serve as a road surface, whereas a bridge is a definite link in a roadway surface. Culverts larger than about 5 to 8 meter span are usually referred to as "soil-steel bridges", to connate the need for greater engineering involvement.

culvert uplift—The upward movement of a culvert end, resulting from hydraulic and buoyancy forces.

cut-end treatment—Refers solely to what is done to the steel inlet or outlet. May be standard pipe bevels, or pipe arch bevels, or skew cuts. Combinations of bevels and skews are not recommended practice. (See end treatment and slope treatment.)

cutoff wall—A wall intended to prevent seepage or undermining (see diaphragm). Usually a buried vertical wall below the end of a culvert.

D

dBA—See weighted decibel.

deadman—Buried anchorage for a guy, cable, etc. Commonly used in retaining walls, cutoff walls, piling and other designs.

debris—Any material including floating woody materials, and other trash, suspended and moved by a flowing stream.

degradation—The progressive general lowering of a stream channel by erosion, other than that caused by a constriction.

depression storage—The fraction of precipitation that is trapped in depressions on the surface of the ground, with the only outlet through infiltration or evaporation.

depth-of-cover—The vertical distance between the profile grade and the crown. Serves as basis for calculation of dead load on structure.

depth-of-scour—The depth of material removed from a stream bed by scour, measured below the original bed elevation.

design discharge—A quantity of flow that is expected at a certain point as a result of a design storm, or flood frequency. Usually expressed as a rate of flow in cubic feet per second, or cubic meters per second. Also the discharge which a structure is designed to accommodate without exceeding the adopted design constraints.

design frequency—The recurrence interval for hydrologic events used for design purposes. As an example, a design frequency of 50 years means a storm of a magnitude that would be expected to recur on the average of once in every 50 years.

design life—The length of time for which it is economically sound to require a structure to serve without major repairs, or replacement.

design storm—A precipitation event that, statistically, has a specified probability of occurring in any given year (expressed either in years or as a percentage). May also be a particular storm that contributes runoff for which the drainage facilities were designed to handle.

detention storage—Temporary storage of excess runoff in surface ponds, or underground tanks, for the purpose of attenuating excess runoff.

detritus—Rock, gravel, sand, silt or other materials carried by flowing water.

diameter—Inside diameter, measured between inside crests of corrugations.

diaphragm—A metal collar at right angles to a drain pipe for the purpose of retarding seepage or the burrowing of rodents. Often specified on pipe spillways, or other drainage structures designed to operate under static head, or head ponding at the inlet.

dike—An embankment or wall constructed to prevent flooding.

discharge—The actual volume of water flowing from a drainage structure per unit of time. Usually measured in cubic feet per second or cubic meters per second.

ditch check—Barrier placed in a ditch to decrease the slope of the Bowline and thereby decrease the velocity of the water.

drainage—Interception and removal of ground water or surface water, by artificial or natural means.

drop structure—A structure in a channel or conduit which permits water to drop to a lower level.

dry well—A steel catch basin with open bottom and perforated walls, that is used to store surface runoff for infiltration, or recharge, into the ground.

E

EOS—Equivalent Opening Size, a major parameter in the selection of a filter fabric for use in filtration and separation.

effluent—Outflow or discharge from a sewer or sewage treatment equipment.

ellipsed—With reference to structural plate corrugated steel pipe, factory-formed to an elliptical shape. May be vertical or horizontal ellipse. Term "elongated" usually refers to a 5% vertical ellipse shape.

embankment (or fill)—A bank of earth, rock or other material constructed above the natural ground surface.

embedment—The depth to which a culvert invert is embedded below the natural stream bed.

end area—The area calculated on the basis of inside diameter (See diameter); or the available flow area through the conduit.

end section—Flared metal attachment on inlet and outlet of a culvert to prevent erosion of the roadbed, improve hydraulic efficiency, and improve appearance. See Index.

end treatment—The overall design of a culvert inlet and/or outlet. This may involve channel treatments, cut end treatments, slope treatments, headwalls, anchorage, etc.

energy dissipator—A structure used to dissipate the energy possessed by high-velocity flow at the outlet of a culvert.

energy grade line—A hydraulic term used to define a line representing the total amount of energy available at any point along a water course, pipe, or drainage structure. Where the water is motionless, the water surface would coincide with the energy grade line. As the flow of water is accelerated the water surface drops further away from the energy grade line. If the flow is stopped at any point the water surface returns to the energy grade line. The energy grade line is established by adding together the potential energy as the water surface elevation (referenced to a datum); and the kinetic energy (usually expressed as a velocity head), at points along the channel or conduit profile.

energy gradient—Slope of a line joining the elevations of the energy head of a stream.

energy head—The elevation of the hydraulic gradient at any section, plus the velocity head.

engineered soil—A selected soil of known properties placed around a conduit in a prescribed manner.

entrance head—The hydraulic head required to cause flow into a conduit; it includes both entrance loss and velocity head.

entrance loss—The head lost in eddies and friction at the conduit inlet.

equalizer—A culvert placed where there is no channel but where it is desirable to have standing water at equal elevations on both sides of a fill.

equivalent diameter—The diameter of a round corrugated steel pipe from which a pipe arch or other shape is formed.

erosion—Wear or scouring caused by hydraulic traffic or by wind.

F

fabricator—A manufacturer of corrugated steel pipe or structural plate corrugated steel pipe product, or other steel construction products. Premises of a manufacturer are referred to as the fabricating plant.

face section—The upstream face of the enlarged and fully enclosed opening of an improved inlet.

fall—A steeply inclined length of channel in or immediately upstream from a culvert inlet to improve hydraulic capacity.

fan duct—Mine ventilation system in which a conduit extends from the ventilating fan to the portal of the fresh air tunnel or air shaft.

fiber-bonded protected corrugated steel pipe—A mill product in which an aramid nonwoven fabric is embedded in the zinc coating, followed by asphalt coating.

filter—Granular material placed around a subdrain pipe to facilitate drainage and at the same time strain or prevent the admission of silt or sediment.

filter cloth—See geotextiles.

fishway—A facility to permit fish to pass an obstruction with minimum stress.

flap gate—A hinged watertight flap covering the outlet of a culvert to allow outflow from the culvert but prevent backflow resulting from higher flood stages downstream.

flexibility factor (FF)—Relative elastic deflection of a conduit. See Chapter. 4, Structural Design. Equation 9.

flood—A relatively high flow, in terms of either water level, or discharge.

flood plain—The relatively level land which adjoins a water course, and which is subject to periodic flooding, unless protected artificially by a dike, or similar structure.

flood routing—An analytical technique used to compute the effects of system storage (i.e. detention ponds); and system dynamics on the timing and shape of a flood wave at recessive points along a stream or channel.

flow area—See end area.

flume—An open channel or conduit of metal, concrete or wood, on a prepared grade, trestle or bridge.

ford—A shallow place where a stream may be crossed by traffic.

foundation—That portion of a structure (usually below the surface of the ground) which distributes the pressure to the soil or to artificial supports. Footing has similar meaning.

foundation drain—A perforated CSP, or a system of CSP subdrains which collects ground water from the foundation or footings or engineered structures, for the purpose of draining unwanted waters away from such structures.

freeboard—The height from a design water level to the top of an embankment, roadway, dam or wall.

free field overburden pressure— The vertical earth pressure at a level in a semi-infinite mass, due to the load of earth and other materials above that level.

free outlet—(as pertaining to critical flow)—Exists when the backwater does not diminish the discharge of a conduit.

free water—Water (in soil) free to move by gravity (in contrast to capillary or hydroscopic moisture).

G

gabion—A steel wire mesh basket filled with stones or broken concrete, and forming part of a larger unit of several such baskets, usually for channel or end treatment, for erosion or scour control, or other purposes.

gage—Reference system for thickness of metal sheets or wire (and bearing a relation to the weight of the metal).

gaskets—A thin sheet of rubber, sheet metal, or other materiel forming a joint between two pieces of metal to prevent leakage. Gaskets for corrugated steel pipe are O-ring, sleeve, or strip type.

geotextiles—Woven or nonwoven engineering fabrics that act as separators to keep soil or fines out of a subdrainage piping system while serving as a filter to allow free flow of water.

gradation—Sieve analysis of aggregates.

grade—Profile of the center of a roadway, or the invert of a culvert or sewer. Also refers to slope, or ratio of rise or fall of the grade line to its length. (Various other meanings)

grade separation—A corrugated steel structure, usually structural plate, installed to allow passage of a road or railroad over another road or railroad. An underpass.

gradient (slope)—The rate of rise or fall of a grade—expressed as a percentage or ratio as determined by a change in elevation to the length.

granular—Technical term generally describing the uniformity of grain size of gravel, sand or crushed stone.
groin—A jetty built at an angle to the shore line, to control the waterflow and currents, or to protect a harbor or beach.

ground water table (level)—Upper surface of the zone of saturation in permeable rock or soil. (When the upper surface is confined by impermeable rock, the water table is absent.)

grout—A fluid mixture of cement, sand, and water that can be poured or pumped easily.

guiderail—A barrier located along the edge of a roadway shoulder for the purpose of guiding errant vehicles onto the roadway.

H

haunch—The portion of the conduit cross-section between the spring line and the top of the bedding or footing.

head (static)—The height of water above any plane or point of reference. (The energy possessed by each unit of weight of a liquid, expressed as the vertical height through which a unit of weight would have to fall to release the average energy possessed.) See Chapter. 3, Hydraulics. Standard unit of measure shall be the foot. Relation between pressure expressed in psi and feet of head is:

$$\text{Head in feet} = \frac{\text{psi x } 144}{\text{Density in}^{\text{lb/cu ft}}}$$

for water at 68° F
1 psi = 2.310 ft.

headwall—A wall (of any material) at the end of a culvert or drain to serve one or more of the following purposes: to protect fill from scour or undermining, increase hydraulic efficiency, divert direction of flow, and/or serve as a retaining wall. Usually a separate vertical cutoff wall at the inlet, or outlet. May be square end, or wing wall, or cribwall design of varying heights; and in a steel, concrete, or masonry. Usually constructed or installed before or during backfill. A partial headwall is less than the full rise of the culvert. (See also end treatment, slope treatment, cutoff wall, cut-end treatment and improved inlet.)

headwater elevation—The water level upstream from a structure.

heat manifold—A corrugated steel pipe installed in an aggregate pile to allow passage of heat to help obtain satisfactory working and setting properties in concrete.

height of cover (HC)—Distance from crown of a culvert or conduit to (1) for highways, bottom of flexible pavement or top of rigid pavement (2) for railways, bottom of tie.

high profile arch—A corrugated steel structure with a relatively high rise in relation to span.

hook bolt—A bolt having one end in the form of a hook.

horizontal ellipse—A long span corrugated steel structure with the major diameter horizontal.

hydraulic gradient—A line which represents the relative force available due to the potential energy available. This is a combination of energy due to the height of the water and internal pressure. In an open channel, the line corresponds to the water surface. In a closed conduit, if several openings are placed along the top of the pipe and open end tubes inserted, a line connecting the water levels in the tubes represents the hydraulic grade line.

hydraulic jump—Transition of flow from the rapid to the tranquil state. A varied flow phenomenon that produces a rise in elevation of backwater flow surface. A sudden transition from supercritical flow to subcritical flow, conserving momentum and dissipating energy.

hydraulic radius—The cross-sectional area of a stream of water divided by the length of that part of its periphery in contact with its containing conduit; the ratio of area to wetted perimeter.

hydraulics—That branch of science or engineering which treats the mechanical properties of water or other fluid motion.

hydrogen ion (pH)—Refers to acidity or alkalinity of water or soil. An ion is a charged atom or group of atoms in solution or in a gas. Solutions contain equivalent numbers of positive and negative ions.

hydrograph—A graph of runoff rate, inflow rate, or discharge rate, versus time.

hyteograph—A graph showing average rainfall, rainfall intensities, or rainfall volume over specified areas, with respect to time.

I

ice jam—The choking of a stream channel by the piling up of drift ice at an obstruction or water course constriction.
icing—The gradual accumulation of ice in a channel or culvert, resulting from freezing of ground water seepage over a period of weeks or months.

impervious—Impenetrable. Completely resisting entrance of liquids.

improved inlet—A culvert inlet incorporating geometry refinements, other than those used in conventional culvert practice, for the purpose of improving the culvert capacity. (see headwall)

infiltration—The passage of water into the soil. The term is also used to refer to groundwater entering a sewer system through joints, manholes, etc. infiltration is not usually desirable in sanitary sewer systems, but may be desirable in urban storm drain systems to control groundwater table, and protect roadway pavements.

inflow—The water discharged into a sewer system from all possible sources, but not infiltration.

inlet control—A hydraulic term which indicates that the capacity of the conduit is governed by the quantity of water which the inlet will accept, due to its size and geometry, and the nature and depth of the head pond. Flow control at a culvert in which the capacity is governed by the inlet characteristics and head-water depth only.

inlet time—The time required for runoff to flow from the most remote point of a drainage area to a point where it enters the sewer.

interaction (soil-steel)—The division of load carrying between pipe and backfill and the relationship of one to the other.

intercepting drain—A ditch or trench filled with a pervious filter material around a subdrainage pipe.

invert—That part of a pipe or sewer below the spring line—generally the lowest point of the internal cross section. The stream bed or floor within a structure or channel.

invert paving—The bottom portion of a pipe conduit that is paved with a material to improve flow, erosion and corrosion characteristics. Asphalt is commonly used for CSP products, and wire mesh and concrete for larger structural plate structures.

inverted pear—A long span structure in which the rise is the major dimension.

J

jacking (for conduits)—A method of providing an opening for drainage or other purposes underground, by cutting an opening ahead of the pipe and forcing the pipe into the opening by means of horizontal jacks.

L

lateral—A conduit diverting water from a main conduit, for delivery to distributaries; a secondary ditch.

lift—One layer of soil material placed in the backfilling process.

liner plate—Formed steel unit used to line or reinforce a tunnel or other opening.

lock seam—Helical seam in a pipe, formed by overlapping or folding the adjacent edges.

low profile arch—A long span structure in which the span is the major dimension.

luminaire—In highway lighting, a complete lighting device consisting of a light source, plus a globe, reflector, refractor, housing. and such support as is integral with the housing. The light standard (bracket or pole) is not considered a part of the luminaire.

M

major system—The route followed by storm runoff when the minor system is either inoperative or inadequate. It generally consists of roads, swales, and major drainage channels. The major system is generally designed to provide 25 to 100 yr. protection against surface flooding.

manhole—Opening from street surface to provide entry for inspection and cleaning of sewer lines.

Manning's Formula—An equation for the value of coefficient C in the Chezy Formula, the factors of which
are the hydraulic radius and a coefficient of roughness.

mean velocity—Average velocity within a stream or conduit cross section.

median—The portion of a divided highway separating roadways.

median barrier—A double-faced guiderail in the median or island dividing two adjacent roadways.

metallic coating—A zinc or aluminum coating applied to corrugated steel pipe for corrosion protection.

minor system—The traditional storm runoff design of storm sewers, street gutters, roof leader connections, foundation drains, etc.—designed to convey runoff from frequent, less intense storms, to eliminate or minimize inconvenience in the area to be developed. (See major system.)

miter cut—An angle in the barrel. A wedge section is cut from the barrel, and the barrel welded to provide a change in alignment. Permits pipe curvature, or changes in grade and/or alignment.

mitered end—A culvert end the face of which conforms roughly with the face of the embankment slope. (see also the preferred term "beveled end")

N

nestable pipe—Half round corrugated steel pipe segments joined by interlocking notches or mating flanges. Primarily used for encasing existing utility or other lines.

noise barriers—All-steel sound reflective barrier located between the source of noise and the desired quiet zone.

nominal thickness—The order thickness for the steel sheet or plate.

normal design flood—The design flood used for the hydraulic design of structures, in the absence of imposed criteria, such as the regulatory flood.

normal water level—The average summer water level. The free surface associated with flow in natural streams.

O

open channel—A drainage course which has no restrictive top. It is open to the atmosphere and may or may not permit surface flow to pass over its edge and into another channel in an unrestricted manner. In many cases where dikes or beams are constructed to increase channel capacity, entrance of surface waters is necessarily controlled.

outfall (outlet)—In hydraulics, the discharge end of drains and sewers.

outlet control—Flow control at a culvert in which the capacity is governed principally by the barrel roughness, length and slope, and in some cases by the tailwater.

P

parapet—Wall or rampart, chest high. Also, the wall on top of an abutment extending from the bridge seat to the underside of the bridge floor and designed to hold the backfill.

paved invert—A smooth asphalt pavement that completely fills the corrugations of the lower segment of a pipe; intended to provide resistance to erosion, and to improve flow.

pear—See inverted pear.

perforated pipe—A corrugated flood used for the steel pipe product with perforations completely through the pipe walls.

> **fully perforated**—A pipe with perforations around the periphery, usually for recharge to ground of storm water.
>
> **invert-perforated**—A pipe with perforations in the lower segment, usually for subdrainage.

performance curve—A plot of discharge versus headwater elevation or depth at a culvert.

periphery—Circumference or perimeter of a circle, ellipse, pipe arch, or other closed curvilinear figure.

permeability—A property of soils which permits free passage of any fluid. Permeability depends on grain size, void ratio, shape and arrangement of pores. Often referred to as penetrability.

pervious—Applied to material through which water passes relatively freely. (i.e. sands and gravels)

pile, bearing—A member driven or jetted into the ground and deriving its support from bearing on the underlying strata and/or by the friction of the ground on its surface. (See also Sheeting)

pipe—A culvert having a non-rectangular cross-section, often assumed to be circular unless specified otherwise.

pipe arch—A corrugated steel pipe or structural plate corrugated steel pipe shaped to a span greater than rise; a multi-radius shape with an arch-shaped top and a slightly convex integral bottom, structurally continuous with an invert whose radius of curvature is greater than that of the crown.

piping—Subsurface erosion caused by the movement or percolation of water fill, or natural ground.

plate—A flat-rolled steel product. See structural plate.

polymeric coating—A plastic coating, bonded to one or both sides of the CSP sheet, prior to fabricating into pipe.

pending—The use of water to hasten the settlement of an embankment—requires the judgment of a soils engineer. In hydraulics, ponding refers to water backed up in a channel or ditch as the result of a culvert of inadequate capacity or design to permit the water to flow unrestricted.

precipitation—Process by which water in liquid or solid state (rain, sleet, snow) is discharged out of the atmosphere upon a land or water surface.

profile grade—The top of the finished granular base of the centerline of the highway or railway.

projecting end—A culvert end which protects from the face of the embankment.

protective coating—A coating applied to the pipe in addition to the standard zinc protection, such as asphalt, polymeric, and aramid fibers.

R

rational method—An empirical approach to estimate storm runoff, by use of the formula Q = CIA, where C is coefficient describing the runoff potential of a drainage area. I is the rainfall intensity during the core time of concentration and A is the drainage area.

re-entrant arch—An arch with haunches.

reformed end—Annular corrugations rolled onto the ends of helically corrugated steel pipe.

regulatory flood—A flood designated for a specific site by a regulatory jurisdiction. or agency, generally for flood plain management purposes.

relief flow—A portion of a major flood which bypasses the main structure at a stream crossing, by flowing over the roadway, or through a relief bridge or culvert.

retaining wall—A wall for sustaining the pressure of earth or filling deposited behind it.

return period—The average period in years between occurrences of a discharge equalling or exceeding a given value.

revetment—A wall or a facing of wood, willow mattresses, steel units, stone, or concrete placed on stream banks to prevent erosion.

Reynolds' Number—A non-dimensional coefficient used as a measure of the dynamic scale of a flow.

ring compression—The principal stress in a confined thin circular ring subjected to external pressure.

riprap—Rough stone of various sizes placed compactly or irregularly to prevent scour by water or debris.

rise—The maximum vertical clearance inside a conduit at a given transverse section, usually the centerline.

roadway (highway)—That portion of the highway including the shoulders, for vehicular use. A divided highway has two or more roadways. (railway)—That part of the right of way prepared to receive the track. (During construction the roadway is often referred to as the "grade.")

rodent gate—An appurtenance at the outlet end of a subdrain or other drainage pipe that swings outward to permit flow and detritus to pass, yet prevents the passage into the drainage network of rodents or other animals, whose nesting could block, and render inoperative, the drain system.

roof leader—A drain or pipe that conducts storm water from the roof of a structure downward and into a sewer for removal from the property, or onto or into the ground for seepage disposal.

roughness coefficient (n)—A factor in the Kutter, Manning, and other flow formulas representing the effect of channel (or conduit) roughness upon energy losses in the flowing water.

runoff—That part of precipitation carried off from the area upon which it falls. AIM the rate of surface discharge of the above. That part of precipitation reaching a stream, drain or sewer. Ratio of runoff to precipitation is a "coefficient" expressed decimally.

S

scour—The local lowering of a stream bed by the erosive action of flowing water.

> **general scour**—is that which occurs in a waterway opening as a result of obstruction of the flow.
>
> **local scour**—is that which occurs at a pier or abutment as a result of local obstruction to the flow.
>
> **natural scout**—is the scour of a stream bed resulting from natural phenomena, such as channel meandering.

seam—A joint between two structural steel plates formed by overlapping and bolting them together. Also the join or lap of riveted CSP. Also the join or weld for continuous helical-weld CSP. (see also lock seam)

sediment—Soils or other materials transported by wind or water as a result of erosion.

seepage—Water escaping through or emerging from the ground along some rather extensive line or surface, as contrasted with a spring, the water of which emerges from a single spot.

service tunnel—A conduit connecting two buildings to provide more direct access for employees, products, materials, or utility lines.

shaft—A pit or well sunk from the ground surface into a tunnel for the purpose of furnishing ventilation or access to the tunnel.

sheathing—A wall of metal plates or wood planking constructed to maintain trench wall stability.

sheeting—A wall of metal plates or wood planking to keep out water, or soft or runny materials.

shoulder—The portion of the conduit between the crown and the spring line.

side tapered inlet—An 'improved' inlet having an enlarged face area with the transition to the culvert barrel accomplished by tapering the sidewalls. Both the barrel and the enclosed inlet structure are on the same grade. Usually cast-in-place.

sill—A low wall placed transversely in a culvert or channel level with or slightly above the invert. Often used downstream of the culvert to maintain tailpond level.

sheet flow—Water flowing across a wide, flat paved area such as a highway or parking lot; may result from rainfall or melting ice or snow.

siphon (inverted)—A conduit or culvert with a U or V shaped grade line to permit it to pass under an intersecting roadway, stream or other obstruction.

skew (skew angle)—The acute angle formed by the intersection of the line normal to the centerline of the road improvement with the centerline of a culvert or other structure.

skew number—The angle between the highway centerline and the culvert centerline measured clockwise, and specified in increments of 5.

slide—Movement of a part of the earth under force of gravity.

slope-tapered inlet—A cast-in-place side-tapered inlet, incorporating a fall within the enclosed inlet structure.

slope treatment—Describes what is done to protect the embankment slope from scour or erosion. May be vegetation (i.e. Bermuda grass); grouted masonry or riprap; a "donut" type concrete collar with entrance flare to improve the inlet coefficient, usually from the headwall up over the crown (and usually on bevel ends, with embedded hookbolts in the casting); plus others. Always placed or constructed after backfill.

slotted steel pipe—Corrugated steel pipe with reinforced longitudinal slots at the crown. Used for interception of sheet flow. The system provides an inlet, runoff pipe and grate in a single unit. Pipe can be perforated for use as an underdrain.

smooth-lined asphalt—A smooth asphalt interior lining that completely fills the corrugations in an asphalt coated corrugated steel pipe. (see also spun lining)

soffit—The bottom of the top of a pipe. In a sewer pipe, the uppermost point on the inside of the structure. The crown is the uppermost point on the outside of the pipe wall.

soil liquefaction—Loss of strength of a soil resulting from the combined effects of vibrations and hydraulic forces, thereby causing the material to flow.

soil-steel structure—A bridge, comprised of structural steel plates and engineered soil, designed and constructed to induce a beneficial interaction of the two materials.

span—Horizontal distance between supports, or maximum inside distance between the sidewalls.

speller—Zinc or galvanized coating on steel products.

spillway—A low-level passage serving a dam or reservoir through which surplus water may be discharged; usually an open ditch around the end of a dam, or a gateway or a pipe in a dam.

- An outlet pipe, flume, or channel serving to discharge water from a ditch, ditch check, gutter or embankment protector.

spread footing—A footing which transfers load directly to the underlying foundation material. Used in structural plate arches.

spring line—The line of the outermost points on the side of a conduit. On a circular pipe, it would be the point one-half of the diameter above the invert. Also, the line of intersection between the intrados and the supports of an arch. Also, the maximum horizontal dimension of a culvert or conduit.

spun lining—An asphalt lining in a pipe, made smooth or uniform by spinning the pipe around its axis.

stable stream grade—The slope of a natural channel at which neither aggradation nor degradation occurs.

Standard Proctor Density—The optimum unit weight of a soil determined in accordance with ASTM designation D-698, or AASHTO T-99.

steady flow—A flow in which the volume passing a given point per unit of time remains constant.

storage basin—Space for detention or retention of storm runoff water for controlled release during or following design storm. Storage may be upstream, downstream, offstream, onstream and/or underground.

storage bin—Built from heavy, curved corrugated steel plates. Used on construction sites and plant storage sides for coal, sand, gravel and other materials.

storm sewer—A sewer that carries only storm water, or clear water runoff.

stormwater management—A master plan, or systems approach to the planning of facilities, programs, and management organizations for comprehensive control and use of stormwater within a defined geographical area.

stream check—A barrier placed in a stream to decrease the slope of the Bowline and thereby the velocity of the water. It is provided with a throat or spillway for dropping the water to a lower level.

stream enclosure—A pipe or other conduit for carrying a stream underground paralleling a roadway or dividing otherwise useful land into smaller parts.

structural plate corrugated steel pipe—Hot-rolled sheets or plate, corrugated, custom hot-dipped galvanized, curved to radius, assembled, and bolted together to form pipes, pipe arches, and other shapes.

subcritical flow—Flow at velocities less than critical, or with a Froude number less than one. In this state, the role played by gravity forces is more pronounced. so the flow has a low velocity, and is often described as steady, tranquil, or streaming.

sub drain—A previous backfilled trench containing a pipe with perforations or open joints for the purpose of intercepting ground water or seepage.

subdrainage—The control of groundwater. Subdrainage helps maintain stable subgrades and structure foundations, eliminates wet cuts and prevents frost heave.

subgrade—The surface of a portion of the roadbed on which paving, or railroad track ballast, or other structure is placed.

supercritical flow—Flow with a Froude number greater than one. In this state, the inertia forces become dominant, so the flow has a high velocity, and is usually described as rapid or shooting.

surcharge—The flow condition occurring in closed conduits when the hydraulic grade line is above the crown of the sewer.

T

tailwater—The water just downstream from a structure.

tailwater depth—The depth of water immediately downstream from a culvert, measured from the invert of the culvert outlet.

threading—The process of installing a slightly smaller pipe or arch within failing drainage structure.

throat section—The intersection of cast-in-place sidewall tapers and culvert barrel in a side—or slope-tapered 'improved' inlet.

thrust—The circumferential compressive force in the conduit walls, per unit length of conduit.

time of concentration—The time required for storm runoff to flow from the most remote point, of a drainage area to the point under consideration. It is usually associated with design storm.

toe drain—A subdrain installed near the downstream toe of a dam or levee to intercept seepage.

transverse section—A section in the vertical plane normal to the horizontal projection of the longitudinal direction.

trash rack—A pervious barrier constructed to catch debris, and prevent blockage of the inlet of a drainage conduit.

trunk (trunk line)—In a roadway or urban drainage system, the main conduit for transporting the storm waters. This main line is generally quite deep in the ground so that laterals coming from fairly long distances can drain by gravity into the trunk line.

tunnel lining—Added inner surface of a tunnel; can be concrete, brick, or steel. A bolted metal shell serving either as a permanent inner surface for a tunnel or as a form by which a concrete wall coating is built.

U

underdrain—See sub-drain.

undermining—A process of scour by hydraulic action that progressively removes earth support from an engineered structure. Undermining is commonly found at the outlet of a culvert or sewer.

underpass—An opening under a roadway to allow pedestrians, livestock, or other traffic to pass in safety. Also an opening under a railroad or other roadway through which a street, highway, or railroad passes.

uniform flow—Flow in which the velocities are the same in both magnitude and direction from point to point along the stream or conduit, all stream lines being parallel.

unsteady flow—A flow in which the velocity changes with respect to both space and time.

utilidor—Utility corridor. See utility conduits.

utility conduits—Conduit installed for the protection of water, steam and gas lines, sewers, or power cables passing underneath a building, roadway, or other obstacle.

V

value analysis—Objective analysis of the features and benefits of corrugated steel pipe in relation to a specified alternate.

velocity head (symbol H_v)—For water moving at a given velocity, the equivalent head through which it would have to fall by gravity to acquire the same velocity.

vertically ellipsed pipe—An elliptical conduit with major diameter vertical and not less than 1.10 times the minor diameter.

ventilation ducts—A conduit installed to provide various degrees of ventilation to protect against health hazards arising from nontoxic gasses, heat, dust, or moisture.

void forms—A corrugated steel tube installed in the concrete deck of a bridge to reduce the amount of concrete used and the overall weight of the deck.

W

wale—Guide or brace of steel or timber, used in trenches and other construction.

washout—The failure of a culvert bridge, embankment or other structure resulting from the action of flowing water.

water course—A natural or artificial channel in which a flow of water occurs, either continuously or intermittently. Natural water courses may be either on the surface, or underground.

water table—The upper limit of the portion of ground wholly saturated with water.

watershed— Region or area contributing to the supply of a stream or lake; drainage area, drainage basin, catchment area.

weighted decibel (dBA)—The most commonly used environmental noise unit. The A indicates that a frequency weighing has been applied within the sound measuring instrument to approximate the sensitivity of the human ear.

weir crest—The point of intersection of the upstream channel slope and the fall slope.

wetted perimeter—The length of the wetted contact between the water prism and the containing conduit, (measured along a place at right angles to the conduit).

Z

zero runoff increase—A concept in which the peak rate of storm runoff from a new urban development is limited to that which occurred prior to development.

zinc coating—A galvanic, barrier coating applied to the surfaces of steel sheet, plate, or other components.

SYMBOLS

Various disciplines of engineering, hydraulics, physics, chemistry, etc. have established standard symbols or letters to denote various factors or dimensions in formulas, tables, drawing and texts. Some of these are found in dictionaries; others have been published by technical associations. Some of the symbols used in this handbook are listed here. For others, reference should be made to sources such as are listed for the preceding Glossary.

Symbol	Definition or Use
a	Area, cross-sectional, culvert,
a	Constant in an Intensity-Duration Frequency Curve,
A	Area, cross-sectional, of waterway, ft^2,
A	Area of long span structure, ft^2,
A	Drainage area, acres,
A	Area of section, $in.^2$,
A	Width of roadway surface or roadbed in determining culvert length,
A	Required wall area,
A	Cross-sectional area of flow in ft^2 at right angles to the direction of flow,
A	Area to be subdrained, acres,
A	Cross-sectional area of liner plate, $in.^2/ft$,
A_c	Partial flow area,
b	Constant in an Intensity-Duration Frequency Curve,
b	Bottom width of a trapezoidal channel,
b	Developed width factor,
B	Invert to spring line,
B	Slope width from roadway to top of culvert on a flat grade,
B	Long span structure length, ft.
B_1	Slope width from roadway to top of upstream end of culvert on a steep grade,
B_2	Slope width from roadway to top of downstream end of culvert on a steep grade,
c	Constant in an Intensity-Duration Frequency Curve,
c	Coefficient of roughness whose value depends on the surface over which water flows,
C	Coefficient, runoff,
C	Compression in pipe wall,
℄	Centerline,
C	Long span dimension between centers of inside radii,
C	Ring compression, thrust, Ib/ft,
C	Elevation from bottom of culvert to top of roadway,
C	Subsurface runoff factor, ft^3/sec,
C_a	Recommended antecedent precipitation factor for the rational formula,

Symbol	Definition or Use
C_d	Soil coefficient for tunnel liner,
C_1	Difference in elevation from roadway surface to top of the upstream end of a culvert on a steep grade,
C_2	Difference in elevation from roadway surface to the top of the downstream end of a culvert on a steep grade,
CO	Carryover design for slotted drain pipes,
d	Depth of channel,
d	Depth of flow in gutter,
d_c	Critical depth,
d	Internal diameter of pipe, ft.
D	Diameter of conduit, inside—or maximum span,
D	Depth of corrugation, in.,
D	Minimum cover from top surface of flexible pavement to corrugated steel pipe for airplane wheel loads,
D	Horizontal diameter or span of a tunnel,
D	Long span structure height, ft.
D_c	Critical pipe diameter, in.,
D	Delta, tangent angle, corrugation,
DL	Dead load,
E	Modulus of elasticity, lb/in.^{2},
E	Railroad live load, Cooper,
EOS	Equivalent Opening Size, geotextiles,
f	Friction factor,
f	The rate of infiltration at a specific period of time,
FF	Flexibility factor,
FS	Factor of safety for buckling,
f_a	Allowable wall stress, lb/in.^{2},
f_c	Compressive stress, lb/in.^{2},
f_c	Minimum rate of infiltration,
f_c	Buckling stress, lb/in.^{2},
f_o	Initial rate of infiltration,
f_u	Minimum specified tensile strength, lb/in.^{2},
v	Poisson's ratio,
g	Gravitational acceleration,
h	Height of fill over pipe,
H	Drop of weir notch, ft.
H	The difference in elevation between the most remote point on the basin and the outlet,
H	Head, ft.
H	Height of soil over the top of a tunnel,

Symbol	Definition or Use
h_o	Tailwater depth (HW),
H_e	Critical head,
He	Head, entrance loss,
He	Increment of head above the critical head, ft.
Hf	Head, friction loss,
Hv	Velocity head,
H. HC	Height of cover,
HW	Headwater depth,
H20	Highway live load,
i	Intensity, rainfall, in./hr
i	Transverse slope,
I	Imperviousness, relative,
I	Moment of inertia, $in.^4$/unit of width,
I	Intensity, in./hr,
ia	Intensity before peak rainfall,
ib	Intensity after peak rainfall,
k	Long span entrance coefficient,
k	Rate of decrease in rate of infiltration, f, per unit of time,
K	Soil stiffness factor; load factor,
K	Constant equal to l/S_d,
K	Conveyance,
ke	Coefficient of head loss at entrance,
kdg, kp	Coefficients based on long span inlet type,
ko	Outlet loss coefficient,
l	Length of pipe, ft.
l	Length of opening, ft.
L	Length of weir notch, ft.
L	Maximum length of travel of water, ft.
L	Length of culvert, ft.
L_1, L_2, L_3	Lengths used for live load pressure distribution calculations for pipe arches, in.,
L'	Adjusted value for length,
LL	Live load,
LA	Actual length,
LR	Length with no carryover,
m	Long span entrance coefficient,
n	Roughness factor,
n	Storm frequency,

Symbol	Definition or Use
n	Coefficient of roughness of a gutter
n'	Actual value of Manning's n,
N	Circumferential bolt space (= 3π or 9.6 in),
P	Pressure, external load,
P	Corrugation pitch, in. (5 x 1 in. corrugation),
P	The external load on tunnel liner,
PE	Collapse pressure,
P_c	Pressure acting on soil at pipe arch corners, lb/ft^2,
P_{cr}	Critical pressure, lb/in.^{2},
P_l	The vertical load at the level of the top of the tunnel liner due to dead load,
P_d	Design pressure, liner plate,
P_e	Rainfall excess equal to gross rainfall minus evaporation, interception and infiltration,
p_i	π = 3. 1416,
pH	Hydrogen ion concentration,
P_v	Design pressure, lb/ft^2,
P_v	Design pressure, ring compression,
Φ	Diameter,
Φ	Index of recharge based on constant rate of infiltration,
Q	Discharge, ft^3/sec (peak, volume rate of flow, or quantity reaching a drain),
Q_D	Total flow,
Q_O	Flow in a gutter, ft^3/sec,
r	Ratio of time before the peak intensity occurs to total time duration,
r	Radius of gyration,
R	Resistivity, electrical,
R	Hydraulic radius,
R	Ratio of rise to span,
R	Radius of conveyor cover,
R	Radius of curvature in hook bolt,
R	Radius of pipe, in.,
R_b	Radius of bottom (plates),
R_c	Radius of corner (plates),
R_s	Radius of side (plates),
R_t	Radius of top (plates),
R_1	Long-span inside radius,
R_2	Long-span inside radius,

Symbol	Definition or Use
s	Hydraulic gradient of gutter,
S	Span of arch or pipe arch (or maximum horizontal diameter of any shaped structure),
S	Slope (of ground, channel, invert), ft/ft,
S	Slope, equal to H/L where H is the difference in the elevation between the most remote point on the basin and the outlet, ft/ft,
S	Side slope,
S	Section modulus, in^3,
S_o	Slope, bed (at outlet),
SF	Safety factor (or FS),
S_d	Maximum storage capacity of depression,
t	Time.
T, t	Uncoated thickness of sheet or plate, in.,
T_c	Time of concentration of flow,
TL	Tangent length,
TW	Tailwater depth,
T	Thrust per lineal ft.
T	Width of water surface, ft.
t_a	Time after peak,
t_b	Time before peak,
V	Velocity, mean, ft/sec,
V	Volume of storage at any particular time,
V	Mean velocity of flow, ft/sec,
V_a, V_l	Approach velocity,
V_c	Velocity head,
ΣV	Summation of vertical forces in ring compression calculations,
w	Unit weight of soil, lb/ft^3,
W	Width, conveyor cover,
W	Weight of moist soil,
W, WP	Wetted perimeter,
W	Total weight of soil and live loads over a structure,
WS	Water surface,
X	Distance from neutral axis to outer fiber,
z	Transverse slope reciprocal.

CONVERSION tables

Table C-1 Length

United States System

1 ft	=	12 in.
1 yd	=	3ft
1 mi	=	5280 ft
1 nautical mi	=	1.1515 statute mi

Metric Units

10 mm	=	1 cm
100 cm	=	1 m
1000 m	=	1 km (about 5/8 mi)

Equivalents

1 in.	=	2.54 cm, or 25.4 mm (preferred units)
1 ft	=	0.3048 m
1 statute mi	=	1.60935 km
1 nautical mi	=	1.853 km
1 cm	=	0.39370 in.
1 m	=	3.28 ft
1 km	=	3280.83 ft = 0.62137 mi

Table C-2 Area

United States System

1 ft^2	=	144 in.^{2}
yd^2	=	9 ft^2
	=	1296 in.^{2}
1 acre	=	43,560 ft^2
	=	4840 yd^2
1 mi^2	=	640 acres
	=	1 section of land (U.S.)

Equivalents

1 cm^2	=	0.155 in.^{2}
1 m^2	=	10.76 ft^2
	=	1.196 yd^2
1 km^2	=	0.386 mi^2
1 in.^{2}	=	6.45 cm^2
1 ft^2	=	0.0929 m^2
1 yd^2	=	0.836m^2
1 mi^2	=	2.59 km^2

Table C-3 Volume and Capacity

United States System

1 ft^3 water at 39.1 ° F	=	62.425 lbs
1 gal (U.S.)	=	231 $in.^3$
1 gal (imperial)	=	277.274 $in.^3$
1 ft^3 water	=	1728 $in.^3$
	=	7.4805 gal (U . S.)
	=	6.2321 gal (imperial)
1 yd^3	=	27 ft^3
	=	46,646 $in.^3$
1 qt	=	2pt
1 gal	=	4 qt
1 gal (U.S.)	=	0.1337 ft^3
	=	0.8331 gal (imperial)
	=	8.345 lbs
1 bbl	=	31.5 gal
	=	4.21 ft^3
1 bu (U.S.)	=	1.2445 ft^3
1 fl oz	=	1.8047 in^3
1 acre ft	=	43,560 ft^3
	=	1613.3 yd^3
1 acre in.	=	3630 ft^3
1 million gal (U .S .)	=	133 ,681 ft^3
	=	3.0689 acre ft
1 ft depth in 1 mi^2	=	27,878,400 ft^3
	=	640 acre ft

Equivalents

1 $in.^3$	=	16.387 cm^3
1 ft^3	=	0.0283 m^3
1 yd^3	=	0.765 m^3
1 cm^3	=	0.061 $in.^3$
1 m^3	=	35.3 ft^3
	=	1.308 yd^3
1 1.	=	61.023 $in.^3$ (approximately 1 qt)
	=	0.264 gal (U.S.)
	=	0.220 gal (imperial)
1 qt (U.S.)	=	0.946 1.
1 gal (U.S.)	=	3.785 1.

Table C-4 Weight

United States System

1 lb	=	16 oz (avdp)
1 ton	=	2000 lbs
1 long ton	=	2240 lbs
1 lb water at 39.1 ° F	=	27.681 in.^{3}
	=	0.016 ft^3
	=	0.1198 gal (U.S.)
	=	0.4536 1.

Equivalents

1 kg	=	2205 lb (avdp)
1 metric ton	=	0.984 long ton
	=	1.102 ton
1 oz (avdp)	=	28.35 gm
1 lb (avdp)	=	0.4536 kg

Table C-5 Pressure

Comparison of Heads of Water with Pressures in Various Units

1 ft water, 39.1 ° F	=	62.425 lbs/ft^2 (psf)
	=	0.4335 lb/in^2 (psi)
	=	0.0295 at.
	=	0.8826 in. mercury at 30° F
	=	773.3 ft air at 32° F and atmospheric pressure
1 ft water at 62° F	=	62.335 lbs/ft^2
	=	0.433 lb/in^2
1 lb water on the in.^{2} at 62° F	=	2.3094 ft water
1 oz water on the in.^{2} at 62° F	=	1.732 in. water
1 at. sea level (32° F)	=	14.697 lbs/in.^{2}
	=	29.921 in. mercury
1 in. mercury (32° F)	=	0.4912 lb/in.^{2}

Table C-6 Flowing Water

cfs	=	ft^3/sec
gpm	=	gal/min
l cfs	=	60 ft^3/min
	=	86,400 ft^3 per 24 hrs
	=	448.83 gal/min (U.S.)
	=	646,317 gal per 24 hrs (U.S.)
	=	1.9835 acre-ft per 24 hrs (usually taken as 2)
1 cfs	=	1 acre-in./hr (approximately)
	=	0.0283 m^3/sec
1 gpm (U.S.)	=	1440 gal per 24 hrs (U.S.)
	=	0.0044 acre-ft per 24 hrs
	=	0.0891 Miners' In., Arizona, California
1 million gal/day (U.S.)	=	1.5472 cfs
	=	3.07 acre-ft
	=	2.629 m^3/min

Table G-1 Areas of Plane Figures

Triangle:	Base × ½ perpendicular height
	$\sqrt{s(s-a)\ (s-b)\ (s-c)}$
	s = ½ sum of the three sides a, b and c
Trapezium:	Sum of areas of the two triangles
Trapezoid:	½ sum of parallel sides × perpendicular height
Parallelogram:	Base × perpendicular height
Regular Polygon:	½ sum of sides × inside radius
Circle:	πr^2 = 0.78540 × dia² = 0.07958 × circumference²
Sector of Circle:	$\frac{\pi r^2 A^\circ}{360} = 0.0087266\, r^2 A^\circ$ = arc × ½ radius
Segment of Circle:	$\frac{r^2}{2}\left(\frac{\pi A^\circ}{180} - \sin A^\circ\right)$

Circle of same area as square: diameter = side × 1.12838

Square of same area as circle: side = diameter × 0.88623

Ellipse:	Long diameter × short diameter × 0.78540
Parabola:	Base × ⅔ perpendicular height

Table G-2 Trigonometric Formulas

Radius, $1 = \sin^2 A + \cos^2 A$

$= \sin A \operatorname{cosec} A = \cos A \sec A$

$= \tan A \cot A$

Sine $A = \frac{\cos A}{\cot A} = \frac{1}{\operatorname{cosec} A} = \cos A \tan A$

$= \sqrt{1 - \cos^2 A}$

Cosine $A = \frac{\sin A}{\tan A} = \frac{1}{\sec A} = \sin A \cot A$

$= \sqrt{1 - \sin^2 A}$

Tangent $A = \frac{\sin A}{\cos A} = \frac{1}{\cot A} = \sin A \sec A$

Cotangent $A = \frac{\cos A}{\sin A} = \frac{1}{\tan A} = \cos A \operatorname{cosec} A$

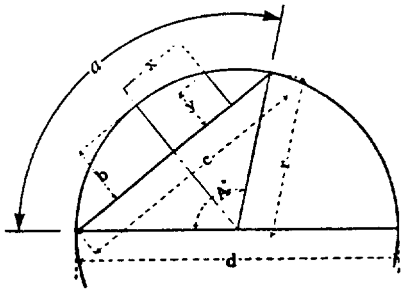
Secant $A = \frac{\tan A}{\sin A} = \frac{1}{\cos A}$

Cosecant $A = \frac{\cot A}{\cos A} = \frac{1}{\sin A}$

Table G-3 Properties of the Circle*

Circumference of Circle of Diameter 1 = π = 3.14159265
Circumference of Circle = 2 π r
Diameter of Circle = Circumference x 0.31831

Diameter of Circle of equal periphery as Square	=	side	x	1.27324
Side of Square of equal periphery as Circle	=	diameter	x	0.78540
Diameter of Circle circumscribed about Square	=	side	x	1.41421
Side of Square inscribed in Circle	=	diameter	x	0.70711



Arc, $a = \frac{\pi r A^\circ}{180} = 0.017453\, r A^\circ$

Angle, $A = \frac{180^\circ a}{\pi r} = 57.29578 \frac{a}{r}$

Radius, $r = \frac{4 b^2 + c^2}{8 b}$ Diameter, $d = \frac{4 b^2 + c^2}{4 b}$

Chord, $c = 2\sqrt{2 b r - b^2} = 2 r \sin \frac{A^\circ}{2}$

Rise, $b = r - \tfrac{1}{2}\sqrt{4 r^2 - c^2} = \frac{c}{2} \tan \frac{A^\circ}{4} = 2 r \sin^2 \frac{A}{4}$

Rise, $b = r + y - \sqrt{r^2 - x^2}$ $y = b - r + \sqrt{r^2 - x^2}$ $x = \sqrt{r^2 - (r + y - b)^2}$

$\pi = 3.14159265$, $\log = 0.4971499$

$\frac{1}{\pi} = 0.3183099$, $\log = \bar{1}.5028501$

$\pi^2 = 9.8696044$, $\log = 0.9942997$

$\frac{1}{\pi^2} = 0.1013212$, $\log = \bar{1}.0057003$

$\sqrt{\pi} = 1.7724539$, $\log = 0.2485749$

$\sqrt{\frac{1}{\pi}} = 0.5641896$, $\log = \bar{1}.7514251$

$\frac{\pi}{180} = 0.0174533$, $\log = \bar{2}.2418774$

$\frac{180}{\pi} = 57.2957795$, $\log = 1.7581226$

*From Carnegie's "Pocket Companion."

Table G-4 Standard Gages for Sheet and Plate Iron and Steel (Black)

Established by Act of Congress, July 1, 1893 (With revisions, 1945)

Number of Gage	Approximate Thickness: Fractions of an Inch, Wrought Iron*	Approximate Thickness: Decimal Parts of an Inch, Wrought Iron*	Approximate Thickness: Decimal Parts of an Inch, Steel†	Approximate Thickness: Millimeters, Steel†	Weight: per Square Foot in Ounces Avoirdupois	Weight: per Square Foot in Pounds Avoirdupois	Weight: per Square Meter in Kilograms
000	3-8	.375	.3587	9.111	240	15.0	73.24
00	11-32	.34375	.3288	8.352	220	13.75	67.13
0	5-16	.3125	.2989	7.592	200	12.50	61.03
1	9-32	.28125	.2690	6.833	180	11.25	54.93
2	17-64	.265625	.2541	6.454	170	10.625	51.88
3	1-4	.25	.2391	6.073	160	10.0	48.82
4	15-64	.234375	.2242	5.695	150	9.375	45.77
5	7-32	.21875	.2092	5.314	140	8.75	42.72
6	13-64	.203125	.1943	4.935	130	8.125	39.67
7	3-16	.1875	.1793	4.554	120	7.5	36.62
8	11-64	.171875	.1644	4.176	110	6.875	33.57
9	5-32	.15625	.1495	3.797	100	6.25	30.52
10	9-64	.140625	.1345	3.416	90	5.625	27.46
11	1-8	.125	.1196	3.038	80	5.0	24.41
12	7-64	.109375	.1046	2.657	70	4.375	21.36
13	3-32	.09375	.0897	2.278	60	3.75	18.31
14	5-64	.078125	.0747	1.897	50	3.125	15.26
15	9-128	.0703125	.0673	1.709	45	2.8125	13.73
16	1-16	.0625	.0598	1.519	40	2.5	12.21
17	9-160	.05625	.0538	1.367	36	2.25	10.99
18	1-20	.05	.0478	1.214	32	2.0	9.765
19	7-160	.04375	.0418	1.062	28	1.75	8.544
20	3-80	.0375	.0359	0.912	24	1.50	7.324

Notes:

By Act of Congress, the gage numbers are based on the weight per square foot in ounce (sixth column) and not on thickness.

* The thickness given in the Congressional table is for wrought iron and not for steel.

† The thickness for steel is from tables compiled by American Iron and Steel Institute, November 1942 based on 41.82 pounds per square foot per inch thick.

- Example: A 16 gage sheet of either wrought iron or steel weighs 40 ounces per square foot. The wrought iron is approximately .0625 inch thick whereas the steel is .0598 inch thick.

GENERAL index

The scope of this book can best be determined by the Table of Contents on page i. The chapters and prime references are shown in bold face. Tables are indicated by T followed by chapter, table number and page number (T1.1, 41). Items listed in the **Glossary**, page 589, are partly cross-referenced to this **General Index**.