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Chapter 6

STRUCTURAL DESIGN

INTRODUCTION

The design of an urban subsurface drainage system must provide for satisfactory performance of the system throughout the design life. Structural design considerations for each system component are of prime importance to system performance. These considerations typically encompass an evaluation of the loading and resultant stresses within the component, and a comparison to service requirements.

This chapter presents discussions on the design methods used for concrete, corrugated steel, and plastic pipe, and an overview of structural design considerations for geocomposites. References are provided where necessary for more in-depth analysis.

LOADS

This section discusses types of loads considered in most pipe applications, where the structural design of the pipe is based on the installed system. Other system components, such as geomembranes or geotextiles, can experience their most severe loading during installation and must be designed to withstand those forces.

Loads affecting pipe design can be broadly classified as dead loads and live loads.

DEAD LOADS

Dead, or permanent, loads are constant in magnitude and position throughout the project design life. Dead loads may include soil loads, system component weight, internal fluid weight, foundation loads, and surcharge loads.

Soil Loads

Soil loads can affect vertical and lateral forces on the pipe. The magnitude of load depends on the type of pipe, soil density, burial depth, and relative water table depth. Soil loads usually constitute the primary dead load used in design.

Soil loads are calculated using either the Marston/Spangler or the prism load methods. The method will differ depending on the design method used to analyze pipe. The prism load is defined as the weight of soil directly above the outside span of the system component. The Marston/Spangler method utilizes the prism load as a base (Marston 1930; Schlick 1932; Spangler and Schlick 1953; Spangler 1973; ACPA 1988; AISI 1971; Uni-Bell 1991; ACPA 1993a; ADS Inc. 1984; ASCE 1982; Chambers et al. 1980; ASCE 1993; ASCE 1992).

Lateral forces can be generally taken as one-third of the vertical force. In shallow burials, maximum forces should be evaluated with the lateral force taken as one-quarter of the vertical force and then with the lateral force taken as one-half of the vertical force.

Pipe Weight

Pipe weights can be obtained from the manufacturer. This load contribution is often an insignificant part of the overall load and is typically neglected.

Internal Fluid Weight

Internal fluid weight may need consideration in some instances. Water transported by subsurface drainage pipe can be assumed to have a density of 62.4 pcf (1,000 kg/m^3). It may be appropriate to analyze for maximum forces with the pipe empty and then with the pipe full.

Foundation Loads

Foundation loads are distributed to the pipe through the foundation of a structure built over or near the drainage system.

Surcharge Loads

Surcharge loads can be vertical or lateral loads applied at any time during the project design life.

LIVE LOADS

Live, or additional, loads change in magnitude and direction during and after construction, and throughout the project design life. Examples of live loads include highway and construction vehicles, trains, and aircraft.

Highway Loading

Highway loadings typically used in pipe design are AASHTO H-20 or HS-20 design loading. Light trucks, tractors, maintenance vehicles, or similar loads should also be evaluated. Lighter highway vehicles may be more appropriate for consideration for some subsurface drainage systems. *Standard Specification for Highway Bridges and Structures* (AASHTO 1992) provides additional information.

Construction Vehicles

Construction vehicles may pose a temporary, although severe, live load consideration. Large earthmoving equipment or similar loads, especially in combination with shallow pipe installations, can adversely affect subsurface drainage systems. Precautions such as providing additional cover over the pipe are usually necessary.

Train Loads

The train load typically used in pipe design is the Cooper E-80 loading. This load is not usually involved in subsurface drainage systems, except possibly for conveyance and outlet pipes. See also *Manual of Railway Engineering* (AREA 1993).

Aircraft Loads

Aircraft loads vary widely in both magnitude and load distribution but are standardized for types of aircraft. *Airport Drainage* (FAA 1970) provides guidance on aircraft loadings; aircraft manufacturers can also provide detailed load information.

GENERAL PIPE BEHAVIOR

Pipe can be broadly classified as either flexible or rigid. Although both types work in concert with the backfill material surrounding them to support loads, the way the pipe is designed to respond to those loads differs.

Rigid pipe is sometimes classified as pipe that cannot deflect more than 2% without cracking. Clay and concrete (reinforced and nonreinforced) are common examples. Rigid pipe transmits most of the vertical load through the pipe wall into the bedding so that proper design includes ensuring adequate wall strength and bedding conditions. Clay and concrete pipe are available in several standard strengths that, along with proper backfill, accommodate most installations.

Flexible pipe can move, or deflect, under loads without damage. Examples of flexible pipe are corrugated steel, high density polyethylene (HDPE), and polyvinyl chloride (PVC) products. Deflection allows the load to be transferred to and carried by the backfill. Design procedures include a consideration of both pipe and soil strength.

RIGID PIPE DESIGN

This section presents an overview of the different design methods currently available for concrete pipe. Source documents are provided for reference.

Concrete Pipe Design

There are two concrete pipe installation design methods: the Indirect Design Method and the Direct Design Method. The Indirect Design Method has two variations, the Historical Indirect Design Method and the Standard Installations Indirect Design Method, which may be used for either reinforced or nonreinforced pipe. From the loads on the pipe, the Direct Design Method determines the moment, thrust, and shear stresses in the pipe, which are then used to determine the required reinforcement areas. See also *Concrete Pipe Technology Handbook* (ACPA 1993a).

The Historical Indirect Design Method was developed for trench and embankment installations in the early 1900s by Marston, Spangler, and others, and relates the field strength of the pipe to the three-edge bearing test strength of the pipe by a bedding factor. This method was based on three types of pipe bedding, currently named Class B, C, or D. In later work, a concrete cradle bedding was developed, which is currently named Class A. The limitations of the bedding classes are that they were developed to fit assumed theories for soil support rather than ease and methods of construction, and the bedding materials and compaction levels are not adequately defined. For additional information refer to Spangler (1973, 1950, 1933), FAA (1970), and Marston et al. (1917).

The Standard Installations Indirect Design Method by Heger is similar to the Historical Indirect Design Method, but replaces the Class B, C, and D bedding with four Standard Installations for both trench and embankment installations. The Standard Installations provide an optimum range of soil-structure interaction characteristics by well-defined soil types and compaction levels. See *Concrete Pipe Technology Handbook* (ACPA 1993a), *Lateral Pressures and Bedding Factors* (ACPA 1991), and *Standard Installations and Bedding Factors for the Indirect Design Method* (ACPA 1993b).

The Direct Design Method has been used in some areas to design concrete pipe directly for the buried condition by determining the reinforcement required for the moments, thrusts, and shears resulting from an assumed pressure distribution. The two most common pressure distributions that have been used in the past are the Olander (Olander 1950), and the Paris (Paris 1921), and, in addition, developed over the last decade, is the Heger pressure distribution (ACPA 1993a,b).

Historical Indirect Design Method. After the type of installation and the pipe size are determined, the Historical Indirect Design Method employs a six-step procedure as outlined in the following (ACPA 1988).

Determination of Earth Load. The complex equations of the Marston/Spangler Method were originally solved by the use of various coefficients. The American Concrete Pipe Association computerized the equations, which were solved for a large range of pipe sizes and installation parameters, and presented the results as numerous tables and graphs in the *Concrete Pipe Design Manual* (ACPA 1970).

Determination of Live Load. Tabular and graphical solutions of live loads on buried pipe structures are also presented in the *Concrete Pipe Design Manual* (ACPA 1988), including the AASHTO HS-20 highway vehicle design loading, the AREA Cooper E-80 railway design loading, and the FAA Concorde aircraft loading, which provides the maximum wheel carriage loading for civilian aircraft. AASHTO and others conclude that highway live loadings are negligible when the system component is buried more than 8 ft (2.5 m).

Selection of Bedding Class. A bedding is utilized to distribute the reaction to the vertical load around the lower exterior surface of the pipe, and reduce stress concentrations within the pipe wall. The load that the pipe will support depends on the width of bedding contact and the quality of contact. The four classes of trench beddings and the four classes of embankment beddings are detailed in *Concrete Pipe Design Manual* (ACPA 1988), and other publications.

Determination of Bedding Factor. The bedding factor is the ratio of the strength of the pipe under the installed condition of loading and bedding to the strength of the pipe in the three-edge bearing test. This same ratio was originally named the load factor, but to avoid confusion with the load factor term used in ultimate strength reinforced concrete design, it was more appropriately renamed as the bedding factor.

Spangler (1933)developed the bedding factor concept for both trench and embankment installations. The bedding factor depends on the width and quality of contact between the bedding and the pipe, and the magnitude of the lateral pressure and the portion of the vertical area of the pipe over which it is effective. For embankment installations, Spangler developed a general theory and equations to determine the bedding factor. For trench installations, Spangler neglected the effect of lateral pressures, and established conservative fixed bedding factors for each of the bedding classes.

Trench bedding factors and embankment bedding factor equations are presented in various publications. The trench bedding factors and tabular solutions for the embankment bedding factors are presented in *Concrete Pipe Design Manual* (ACPA 1988).

Application of Factor of Safety. The total earth load and live load is computed and multiplied by a factor of safety to determine the pipe supporting strength required. Since numerous reinforced concrete pipe sizes are available, three-edge bearing test strengths are classified by *D*-loads. The *D*-load concept provides strength classification independent of pipe diameter inches (millimeters). *D*-loads are calculated by dividing the three-edge bearing load in pounds (*N*) by both the inside span and length of the pipe in feet (*m*). The required three-edge bearing test strength of nonreinforced concrete pipe is expressed in pounds per linear foot (*N/m*), not as a *D*-load.

As specified in ASTM (American Society for Testing and Materials) standards on reinforced concrete pipe, the factor of safety is defined as the relationship between the ultimate strength *D*-load strength and the 0.01 in. (0.3 mm) crack *D*-load strength. Consequently, if the 0.01 in. (0.3 mm) crack *D*-load strength is the design criterion, a factor of safety of 1.0 is applied; and, if the ultimate *D*-load strength is the design criterion, the factor of safety is presented in the ASTM standard for the type of pipe being designed (ASTM C76 and ASTM C507). For nonreinforced concrete pipe a factor of safety of 1.25 to 1.5 is normally used (ASTM C14).

Selection of Pipe Strength. ASTM has developed standard specifications for various types and strengths of precast concrete pipe. Each specification contains design, manufacturing, testing, and acceptance criteria.

Computer Programs. The SAMM (Spangler and Marston Method) computer program provides rapid solutions for the Historical Indirect Design Method for concrete pipe. The program can also be used to determine earth loads and live loads for any type of pipe for the trench and embankment conditions (ACPA 1990a).

Standard Installations Indirect Design Method. Through consultations with engineers, contractors, and numerous research studies, four trench Standard Installations and four embankment Standard Installations were developed, and provide an optimum range of soil-structure interaction characteristics. These Standard Installations replace the Class B, C, and D beddings in the Historical Indirect Design Method. After the type of installation and the pipe size are determined, the six-step procedure of the Historical Indirect Design Method is still appropriate (ACPA 1993b).

Determination of Earth Load. Earth loads may be determined using the *Concrete Pipe Design Manual* (ACPA 1988), or calculated with the SAMM computer program (ACPA 1990a).

Determination of Live Load. Live loads may be determined using the *Concrete Pipe Design Manual* or calculated with the SAMM computer program (ACPA 1990a).

Selection of Standard Installation. For well-defined areas at the side and under the pipe, the Standard Installations specify soil classifications using AASHTO and the universal soil classification system (USCS), with required standard and modified Proctor compaction percentages. The selection of a Standard Installation for a project should be based on an evaluation of the quality of construction and inspection anticipated. A Type 1 Standard Installation requires the highest construction quality and degree of inspection. Construction quality and degree of inspection are reduced for Type 2, 3, and 4 Standard Installations, such that a Type 4 Standard Installation requires virtually no construction or quality inspection. Consequently, a Type 4 Standard Installation will require a higher strength pipe, and a Type 1 Standard Installation will require a lower strength pipe for the same depth of burial (ACPA 1993b).

Determination of Bedding Factor. Separate bedding factors for the Standard Installations were developed for earth loads for the trench and embankment conditions, and for live loads. The method of calculating bedding factors and tables of bedding factors are presented in *Standard Installations and Bedding Factors for the Indirect Design Method* (ACPA 1993b).

Application of Factor of Safety. As in the Historical Indirect Design Method, the total earth load and live load is computed and multiplied by a factor of safety to determine the pipe supporting strength required. The *D*-load concept for pipe strength classification is also utilized. The required three-edge bearing test strength of nonreinforced concrete pipe is again expressed in pounds per linear foot (*N/m*), not as a *D*-load.

As specified in ASTM standards on reinforced concrete pipe, the factor of safety is defined as the relationship between the ultimate strength *D*-load strength and the 0.01 in. (0.3 mm) crack *D*-load strength. Consequently, if the 0.01 in. (0.3 mm) crack *D*-load strength is the design criterion, a factor of safety of 1.0 is applied; and, if the ultimate *D*-load strength is the design criterion, the factor of safety is presented in the ASTM Standard for the type of pipe being designed (ASTM C76 and ASTM C507). For nonreinforced concrete pipe a factor of safety of 1.25 to 1.5 is normally used (ASTM C14).

Selection of Pipe Strength. ASTM has developed standard specifications for various types and strengths of precast concrete pipe. Each specification contains design, manufacturing, testing, and acceptance criteria.

Computer Programs. A computer program modifying SAMM for the Standard Installations is being developed and will provide rapid solutions for the Standard Installations Indirect Design Method for concrete pipe. SAMM, however, can be used at this time to determine earth loads and live loads for any type of pipe for the trench and embankment conditions (ACPA 1990a).

Direct Design Method Using Paris or Olander Pressure Distributions. Direct design of buried pipe requires the determination of total load on the pipe and the distribution of earth pressure around the pipe. The Paris and Olander pressure distributions are the two assumptions most commonly used. After the pipe size is determined, a direct design method utilizing the Paris or Olander pressure distribution consists of four steps as follows:

Determination of Total Load. Total load is usually determined by the Marston/Spangler Method.

Selection of Pressure Distribution. The Paris, also called uniform, pressure distribution assumes the vertical loads are uniformly distributed across the top of the pipe; the vertical reaction is uniformly distributed over the horizontal chord of a bedding angle, and lateral loads are distributed either uniformly or trapezoidally over the full or partial height of the pipe (Paris 1921).

The Olander, also called radial, pressure distribution assumes all loads on the pipe act radially on the pipe, varying as a cosine function from a maximum at the crown of the pipe to zero at the edge of the loading angle. Similarly, the reaction at the bottom of the pipe is assumed to act radially, varying as a cosine function from a maximum at the invert of the pipe to zero at the edge of the bedding angle. Another assumption is that the total of the loading angle and the bedding angle extend over the full circumference of the pipe, so that it is only necessary to specify the bedding angle. This latter assumption arbitrarily relates the lateral pressure to the bedding angle (Olander 1950).

Structural analysis. A structural analysis determines the moments, thrusts, and shears around the pipe using an idealized elastic analysis. The stiffness of the pipe is assumed constant and based on the stiffness of an uncracked section without reinforcement. Nondimensional coefficients for moment, thrust, and shear at various points around the pipe wall were developed in terms of the total vertical load and the pipe radius for both uniform and radial pressure distributions (ACPA 1993a).

Design of Reinforcement. A general design procedure for reinforced concrete pipe design is presented in Section 17 of the *Standard Specifications for Bridges and Structures* (AASHTO 1992). The design of reinforcement for concrete pipe is based on the method developed by Heger and McGrath (1982).

Computer Programs. The PIPECAR (pipe culvert analysis and reinforcing design) computer program developed by the Federal Highway Administration provides direct designs of reinforced concrete pipe based on the Marston/Spangler method for loads, the Paris or Olander pressure distributions, and the Heger/McGrath pipe reinforcement design method (FHWA 1989).

Direct Design Using the SIDD Method. The Heger pressure distribution is based on in-depth quantitative simulations of soil-structure interaction using the finite element computer program SPIDA (soil pipe interaction design and analysis) (ACPA 1990c), and on direct tests for pressure distribution. SPIDA was also used to develop the Standard Installations, which are used in the SIDD (Standard Installations Direct Design) method. The SIDD method has been published as ASCE *Standard Practice 15-93* (ASCE 1993). After the type of installation and pipe size are determined, the SIDD method of Direct Design consists of four steps as outlined in the following.

Selection of Standard Installation. For well-defined areas at the side and under the pipe, the Standard Installations specify AASHTO and USCS soil classifications with required standard and modified Proctor compaction percentages. The selection of a Standard Installation for a project should be based on an evaluation of the quality of construction and inspection anticipated. A Type 1 Standard Installation requires the highest construction quality and degree of inspection. Construction quality and degree of inspection are reduced for Type 2, 3, and 4 Standard Installations, such that a Type 4 Standard Installation requires virtually no construction or quality inspection. Consequently, a Type 4 Standard Installation will require a higher strength pipe, and a Type 1 Standard Installation will require a lower strength pipe for the same depth of burial (ACPA 1993b).

For the Heger pressure distribution, nondimensional coefficients were developed for the vertical arching factor, horizontal arching factor, and earth pressure ratios for each type of Standard Installation (Heger and McGrath 1982).

Determination of Loads and Distribution. The prism load is defined as the weight of a column of earth the width of the outside diameter of the pipe above the springline. The prism load times the vertical and horizontal arching factors provides the vertical and lateral forces on the pipe. The earth pressures