Recommendations for Design of Reinforced Concrete Pipe

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Abstract: Currently, two methods are available for the design of reinforced concrete pipes: *the indirect design method* and *the direct design method*. However, changes to indirect design procedures and proper application of the direct design method may not be well understood by designers. The goal of this work is to present designers with a concise history and major concepts of both methods to facilitate the proper application of either method for reinforced concrete pipe. The development of the indirect design method is given with emphasis on changes in the *bedding factor*, which is a constant that relates the strength of pipe in the three-edge-bearing test to the strength of pipe in the installed condition. The development of the standard installations and direct design method are presented, and finally a comparison between design results from both methods is made. Recommendations for reinforced concrete pipe design and the proper application of the bedding factor are provided. The direct design method is promoted as a superior method for the design of reinforced concrete pipe.

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Introduction

Two design methods currently exist for the design of buried reinforced concrete pipe (RCP): the *indirect design method* and the *direct design method*. The direct design method employs advanced structural analysis techniques, modern concepts of reinforced concrete design, and soil characteristics in contrast to the traditional empirical nature of the indirect design approach. However, the writers anticipate that designers will continue to use the indirect design method as long as specifications and supporting materials are published. Unfortunately, some of the concepts that form the basis of the indirect design method are not well understood or correctly used today. One such concept is the *bedding factor*.

The bedding factor relates the strength of pipe in the three-edge-bearing (TEB) test to the strength of pipe in the installed condition and the selection of the bedding factor strongly affects the design results. While this is the case, it is difficult to calculate an accurate bedding factor because the TEB loading condition is very different from the installed condition, and the true bedding factor relationship is complex.

The indirect design method was developed between 1910 and 1930. Changes in engineering practice, technology, and methods of construction have led to modifications in the formulation of the bedding factor to reflect practical advancements while providing more economy and performance in RCP installations. However, modifications to the indirect design procedures are not universally adopted by consulting engineers. Specifications and design aids for several versions of indirect design practice exist and the selection of appropriate design methods by a consultant has become a difficult task in the absence of a unified current design procedure. Development of the direct design method began in the 1970s and continues to the present. Accurate models of the pipe-soil interaction were developed followed by the design of a computer program to perform analysis and design of RCP.

A concise new publication is necessary for designers to understand the available methods and their limitations. In this paper, a thorough review of the pertinent literature is presented and the evolution of the bedding factor is documented. The implications of installation types and the selection and use of bedding factors are discussed. As a result, guidance is provided to practicing engineers for more effective and standardized use of the design methods in general and indirect design bedding factors in particular. The direct design method is promoted as a superior method for the design of RCP.

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Review of Concrete Pipe Design Methods

RCP has been primarily designed using semiempirical techniques for the past century and has shown good performance over the years. In this section, the development of the available design methods for buried concrete pipe is briefly presented in chronological order.

Beginning in 1910, Anson Marston developed a method for calculating earth loads above a buried pipe based on the understanding of soil mechanics at that time. In the late 1920s, a research project at the Iowa State University was conducted with the objective of determining the supporting strength of buried rigid pipes in an embankment installation when subjected to earth

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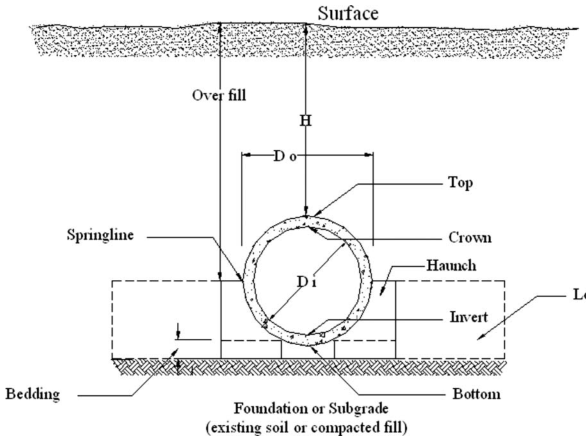

Fig. 1. Standard installation terminology [adapted with permission from *Concrete Pipe Technology Handbook* (ACPA)]

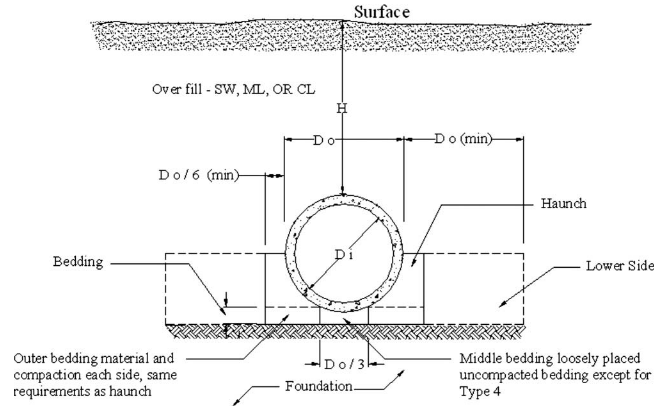

Fig. 2. Standard embankment installation [adapted with permission from *Concrete Pipe Technology Handbook* (ACPA)]

pressures, using Marston's theories. The results of this research were given in a comprehensive paper by M. G. Spangler (1933), where a general equation for the bedding factor was presented. His work included the definition of four standard bedding types that are similar to those defined earlier by Marston. The reader is referred to the literature [American Concrete Pipe Association (ACPA) 1993, 2000] for details of the historic bedding types. Marston and Spangler's works form the basis of the indirect design method currently used for RCP.

According to the indirect design method, the required supporting strength of the pipe is a function of the magnitude of the earth pressure and its distribution around the pipe. Supporting strength is obtained from the results of TEB tests. The required strength is defined in terms of the total load, a bedding factor, and a factor of safety. Wall thickness, concrete strength, and reinforcement requirements corresponding to the required strength are given in ASTM C76 (ASTM 2005).

The indirect design method has been a generally accepted procedure in the past; however, developments in the understanding of soil properties as well as advancements in structural analysis techniques have led to significant improvements in the design of concrete pipe that are not reflected in the indirect design method. In the 1970s, ACPA instituted a long-range research program with the objective of evaluating the performance of concrete pipe-soil installations and improving the design practice. In this research, the structural behavior of concrete pipes and soil-structure interactions were examined. As a result of this research program, new standard installation types and the Heger earth pressure distribution (Figs. 1–4) were recommended, which differ considerably from those originally developed by Marston and Spangler. Consecutively, four new standard installations, Heger earth pressure distribution, and the direct design procedure were incorporated in a 1993 ASCE standard entitled "ASCE standard practice for direct design of buried precast concrete pipe in standard installation (SIDD)" (ASCE 1998). These installations and the Heger pressure distribution will be discussed in detail in a later section.

According to the direct design method, as in the indirect design method, the required supporting strength of the pipe is a function of the magnitude of earth pressure above the pipe and the pressure distribution around the pipe. The required strength of the concrete pipe is determined from the effects of the bending moment, thrust, and shear in the pipe wall. Wall thickness, concrete strength, and reinforcement design are evaluated using rational procedures based on strength and crack width limits that were developed in the ACPA long-range research program.

Currently, both the indirect and the direct design methods are used for the design of RCP, and both methods have elements related to the other. The modern standard installations, which

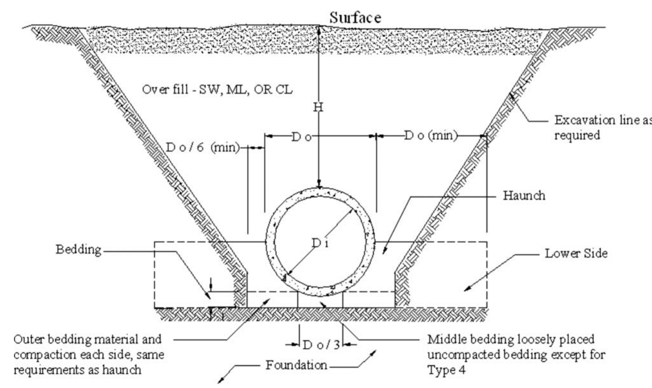

Fig. 3. Standard trench installation [adapted with permission from *Concrete Pipe Technology Handbook* (ACPA)]

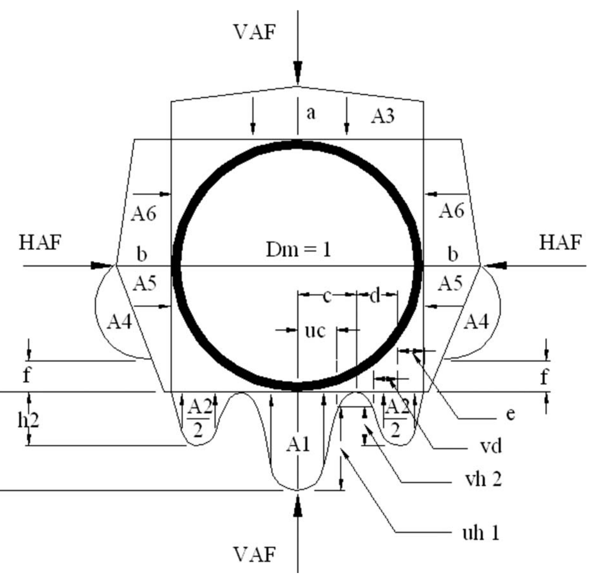

Fig. 4. Heger earth pressure distribution [adapted with permission from *Concrete Pipe Technology Handbook* (ACPA)]

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were developed to eliminate the limitations of the historic installations, and were incorporated in the direct design method, are also used in the indirect design method with acceptable performance. Vertical arching factor, as shown in Fig. 4, generated by Heger earth pressure distribution is also applied to the calculation of earth pressures in the indirect design method. On the other hand, the rational evaluation used for predicting the strength of RCP and crack width limits in the direct design method were developed based on the results of TEB tests, which were originally intended for the indirect design.

Development of the Bedding Factor

The indirect design method of RCP design began with research performed at the Iowa State University in the early 1900s. The Concrete pipe technology handbook published by the ACPA contains a concise history of this work (ACPA 1993). The two objectives of the research were to determine the load on a buried pipe and the supporting strength of the pipe. Anson Marston developed a method for calculating earth loads above a buried pipe. Marston suggested that the supporting strength of pipe should be based on the loading and the type of support given by the specified bedding material. Therefore, to facilitate calculations of the supporting strength of pipe, Marston developed four installation conditions based on theoretical and experimental work. These installation types were named "classes" and rated from D to A, based on the quality of the bedding, as listed below in order of increasing quality (ACPA 1993).

- Class D: hard flat bottom assumed.
- Class C: bottom support over a shaped arc of 60°–90° is assumed with soil placed with ordinary care to give the equivalent of 90° of bottom support.
- Class B: bottom support over a shaped arc of at least 90° with the pipe surrounded by thoroughly compacted soil to at least 15° above the springline.
- Class A: concrete placed around the lower part of the pipe.

Spangler developed the concept of bedding factor through research performed at the Iowa State University in the 1930s. The results of his work were published in a report entitled "The supporting strength of rigid pipe culverts" (Spangler 1933). Spangler concluded that the bedding factor is a function of both the width of contact and quality of contact between the pipe and bedding material. The bedding factor can be expressed as the ratio of the vertical load which causes cracking in the pipe wall in field conditions to the vertical load which causes cracking in the pipe in a TEB test. The TEB test will be explained in the following section. Spangler noted that the first cracks developed at the invert of the pipe during experiments.

According to the indirect design method, the required supporting strength of pipe is based on the bedding factor, the total load, and a factor of safety, as illustrated in Eq. (1). The supporting strength is expressed as a D load to classify strength independent of pipe diameter. The bedding factor is inversely proportional to the required D load

$$D_{\text{load}} = \frac{W}{B_f} \times \frac{\text{FS}}{D} \tag{1}$$

The bedding factor is defined as the ratio of the supporting strength of pipe under the field loading condition (W) to the supporting strength of similar pipe in a TEB test. Because cracking in concrete is a function of tensile stresses in the pipe wall, it can be

Table 1. Traditional Bedding Factors

Bedding class	Embankment, B_{fe}	Narrow trench, B_{ft}
B	2.5–2.9	1.9
C	1.7–2.3	1.5
D	1.1–1.3	1.1

Note: Source: *Concrete Pipe Technology Handbook* (ACPA).

shown (Spangler 1933; ACPA 1991) that the bedding factor can also be expressed as a ratio of moments in the TEB test and field conditions. The fundamental bedding factor relationship is expressed in Eq. (2)

$$B_f = \frac{W}{\text{TEB}} = \frac{M_{\text{test}}}{M_{\text{field}}} \tag{2}$$

Table 1 presents traditional bedding factors for a range of typical embankment conditions and for the trench condition. For an embankment condition (Fig. 2), the bedding factor is also dependent on the magnitude of lateral pressure and the portion of the vertical height of the pipe over which this pressure acts. The embankment bedding factors, B_{fe}, represent a range of factors appropriate for most of the installation conditions expected to be encountered. Lateral pressure causes bending moments in the pipe wall which act opposite to the bending moments resulting from vertical soil pressure. The moments produced by lateral soil pressure are therefore beneficial to the supporting strength of the pipe, as the larger bedding factor corresponds to a smaller required D load for a given installation. The trench bedding factors, B_{ft}, were based on experimental results of test installations and represent conservative values for their respective bedding class. The earliest formulation of the bedding factors for the trench condition ignored any beneficial lateral soil pressure, however, subsequent formulations recognize that it is reasonable to assume some benefits from lateral pressure in the trench condition.

Three-Edge-Bearing Test

The TEB test (Fig. 5) was developed at Iowa State University as an easy and inexpensive way to determine a minimum strength condition for pipe (Peckworth and Hendrickson 1964). It is common practice to use TEB test performance as a quality control criterion for concrete pipe.

The equation for the moment at the invert under a TEB load can be expressed in terms of the applied load and pipe radius [Eq.

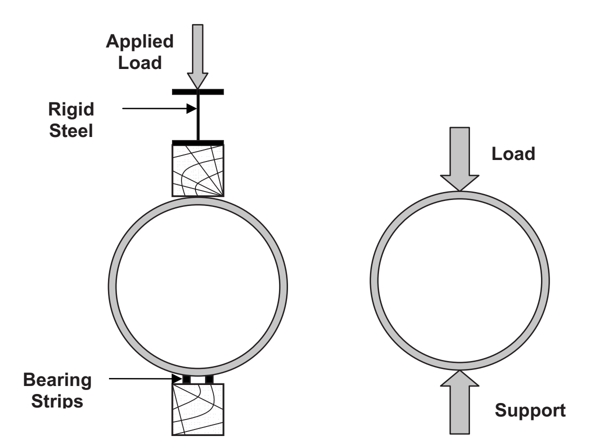

Fig. 5. TEB test and associated pipe loading (B. Skourup)

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(3)] (Spangler 1933; ACPA 1991). The result is used to formulate bedding factors as ratios of invert moments in later documents (ACPA 1991, 1996, 2000)

$$M_A = 0.318PR \tag{3}$$

The loading condition in the pipe wall during a TEB test is much more severe than the loading expected in the installed condition. The vertical loads applied to the top and bottom of the pipe in the test are concentrated loads while the loads in the installed condition will be distributed over some portion of the pipe. Similar to arch shapes, point loads cause larger stresses and deflections in the circular pipe than uniformly distributed loads and an installed pipe will rarely experience concentrated loads. Also, note that as the diameter of pipe increases, the ratio of wall thickness to diameter decreases and the TEB test becomes a more severe loading condition for the pipe (Peckworth and Hendrickson 1964). For larger diameter pipes, shear stresses will govern pipe strength in a TEB test while shear or flexure limit states may control the pipe strength in the field ACPA 1993). Generally, flexure will control for lower fill heights while shear will control for higher fill heights. This is an important consideration because the bedding factor is fundamentally defined as a ratio of TEB load and field load which cause the same effect in the pipe wall. If the controlling limit state in the TEB test does not correspond to the limit state in the field, the bedding factor relationship is a false indication of supporting strength. Additionally, in the case where shear controls both the TEB test and the field condition, the formulation of the bedding factor as a ratio of moments at the invert is inconsistent with the actual behavior of the pipe in the TEB test and the installed condition. Therefore, the use of bedding factors based on moments for this case is inappropriate.

Reformulation to account for Lateral Pressure

The earliest trench bedding factors developed at Iowa State University were derived empirically from test installations without using sidefill and therefore, no lateral soil pressure effects were noted. The embankment bedding factors were developed considering active lateral pressure applied to the sides of the pipe above the top of the in situ soil adjacent to the pipe (ACPA 1993). *Concrete Pipe Info #12* (ACPA 1991) is an ACPA publication that presents improvements for the bedding factor concept, where lateral soil pressure is considered both for trench and embankment installations. Modern construction equipment can provide high levels of backfill compaction that result in passive lateral earth pressures which should be accounted for in the design of RCP. Lateral pressure acting on the pipe will produce bending moments in the pipe wall which act opposite to those bending moments produced by vertical loads and therefore, will reduce the total bending moment within the pipe wall. The lateral pressure also produces an axial thrust component in the wall of the pipe where the maximum moment occurs, which is typically at the pipe invert. Similar to arches, the effect of axial force in a pipe wall is significant in design. Arch structures made of concrete rely on this axial compression for their load carrying capacity. When load effects create a combination of axial force and flexure, the pure compressive stresses created in the cross section due to the axial thrust reduces the flexural tensile stresses and thus are beneficial. Axial compression in these structures is an important consideration because this thrust reduces the tensile stresses in the structure and allows the material to span longer distances. In this formulation of the bedding factor, published in 1991, the benefits of lateral earth pressure on pipe supporting strength are considered. However, the beneficial axial thrust component is conservatively neglected. This formulation is based on the historical bedding classes and involves calculations which require the designer to make several assumptions about the installation characteristics, pressure distribution around the pipe, and soil properties.

Limitations of Indirect Design Using the Historical Bedding Classes

As a result of recent advancements in manufacturing and construction, advanced structural analysis techniques, modern concepts of reinforced concrete design, and soil characteristics, practical issues regarding the economy and state-of-the-art of the indirect design method have developed over the years. These deficiencies of the indirect design method and the historical bedding classes are listed below (ACPA 1993).

- The traditional bedding classes (A, B, C, and D) are not well defined nor do they provide quantifiable standards for the type and compaction of soils.
- These bedding classes are not appropriate for modern construction techniques.
- The traditional soil pressure distributions are not experimentally validated.
- The indirect design method is not flexible in regard to pipe design, i.e., improved material characteristics such as concrete strength, reinforcement yield strength, and other variables cannot be accounted for.
- The limit state of pipe in TEB may be different than the limit state in the installed condition and therefore, the bedding factor relationship based on equivalent loads or equivalent load effects between TEB tests and the installed condition are sometimes invalid.

To address these issues, the ACPA initiated a long-term research program to develop a modern method for designing RCP installations (ACPA 1993). The developments resulting from this research are discussed in the next section.

Development of Standard Installations

The modern installations were developed to include the benefits of advancements in engineering practice and the implementation of computer methods of analysis. The research goals were to improve both the economy and performance of buried RCP installations. Initial research at Northwestern University developed an accurate model of the pipe-soil installation (Krizek and McQuade 1978). The next step was the design of a computer program, SPIDA, that could determine loads and pressure distributions on buried pipe based on user-supplied installation characteristics. Using this information, a designer could implement SPIDA to analyze and design pipe to meet the demands of a particular installation (Hodges and Eyart 1993). Furthermore, a series of parametric studies based on SPIDA analysis led to the specification of four new standard installations that are summarized below in terms of installation (soil type, compaction, and inspection) and pipe supporting strength requirements.

- Type 4 least stringent requirements for installation, highest requirementfor supporting strength.
- Type 3 less stringent requirements for installation, higher requirement forsupporting strength.
- Type 2 more stringent requirements for installation, lower requirement forsupporting strength.
- Type 1 most stringent requirements for installation, lowest re-

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Table 2. Standard Installation Bedding Factors

Installation type	Embankment, B_{fe}	Narrow trench, B_{ft}
2	2.8–3.2	1.9
3	2.2–2.5	1.7
4	1.7	1.5

Note: Source: *Design Data #40* (ACPA).

quirement forsupporting strength.

The parametric studies also led to a single accurate pressure distribution around the buried pipe developed by Heger (Fig. 4). The differences in pressure between the standard installation types are accounted for by nondimensional factors. The Heger pressure distribution and the standard installations have been widely verified by experiments (Selig and Packard 1986, 1987; Sargand et al. 1995; Kurdzeil 1999; Hill et al. 1999; Wong et al. 2006) and allow for the determination of loading configurations for buried pipe in each of the standard installation types. The standard installations have several advantages over the traditional installations (Hodges and Eyart 1993):

- The new installations are quantifiable with regard to the types of soils used and their compaction levels. Quantification of material and compaction requirements eliminate any uncertainty associated with the interpretation of the historical bedding classifications.
- The new installations are far more versatile than the traditional bedding classes. Designers have more choices with respect to the use of native soils, installation effort, and inspection requirements.
- The new installations are conservative, where the embankment loadings (worst case) are used along with traditional AASHTO load factors.
- Voids are conservatively assumed to exist in the haunch zone.

Indirect Design Using Standard Installations

Design Data 40 (ACPA 1996) and the *Concrete Pipe Design Manual* (ACPA 2000) are the newest ACPA publications pertaining to bedding factors. In these documents, the bedding factors are redeveloped for the standard installations and Heger pressure distributions. For the first time, beneficial axial thrust is considered in the development of the bedding factor. The expression for invert moment in the field including axial thrust can be expressed as Eq. (4)

$$M_{\text{field}} = M_{FI} - 0.375N_{FI}t - 0.125N_{FI}c \quad (4)$$

Rewriting Eq. (3) to include the pipe wall thickness yields

$$M_{\text{test}} = M_A = 0.318N_{FS}(D+t) \quad (5)$$

Inserting Eqs. (4) and (5) into Eq. (2) yields Eq. (6)

$$B_f = \frac{M_{\text{test}}}{M_{\text{field}}} = \frac{0.318N_{FS}(D+t)}{M_{FI} - 0.375N_{FI}t - 0.125N_{FI}c} \quad (6)$$

The springline axial thrust in a TEB test, N_{FS}, is equivalent to the springline axial thrust in the installed condition when the applied TEB load equals the resultant of the vertical field load. Using direct design software, the *service load* moments and thrusts (M_{FI}, N_{FI}, and N_{FS}) required for the computation of the bedding factor can be calculated for each installation type through the entire range of available pipe diameters. The resulting bedding factors are presented in Table 2.

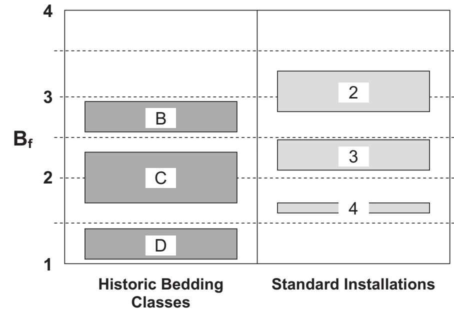

Fig. 6. Embankment bedding factors—comparison (B. Skourup)

The direct design effective moment equation [Eq. (7)] is similar to Eq. (4) and is presented here for comparison

$$M_E = M_U - N_U\left(\frac{h-a}{2}\right) \quad (7)$$

It should be noted that the thrust load factor is 1.0 for ultimate load calculations as it is calculated by the direct design method. Consequently, the effect of thrust on the resulting service moment [Eq. (4)] is greater than the effect on the resulting ultimate moment [Eq. (7)]. Therefore, the indirect design method may overstate the benefit of axial thrust. This correlates to a decrease in the required supporting strength of pipe.

Comparison of Bedding Factors Developed Using Bedding Classes and Standard Installations

Fig. 6 presents a comparison between bedding factors computed for the traditional bedding classes (Table 1) and bedding factors computed using standard installations (Table 2) for the embankment condition. The standard installation bedding factors are larger than the traditional bedding factors. The increase in bedding factor, which corresponds to a decrease in the required *D* load, is due to the inclusion of beneficial axial thrust in the expression for the field moment in the latest formulation of the bedding factor. The standard installations also represent a more accurate model of pipe-soil interaction than the bedding classes. Note that the new standard installation types are not related nor considered equivalent to the traditional bedding classes.

The incorporation of standard installations into the indirect design method provides substantial improvements in the traditional method. However, the standard installations were developed to be used with the newer *direct design procedure,* thus the writers suggest that adopting the direct design method along with the standard installations is clearly a better practice and modern approach to RCP design. The indirect and the direct design methods are compared in more detail in a later section.

Standard Installation Direct Design

The development and experimental verification of the standard installations are previously mentioned. The standard installations can be implemented as a state-of-the-art enhancement to the indirect design method. However, the ACPA research program also developed a modern, flexible, and efficient design procedure (direct design method) to take full advantage of the standard installations. The direct design method permits more accurate design of pipe and evaluation of pipe structural behavior using design procedures that are similar to those used for other reinforced concrete

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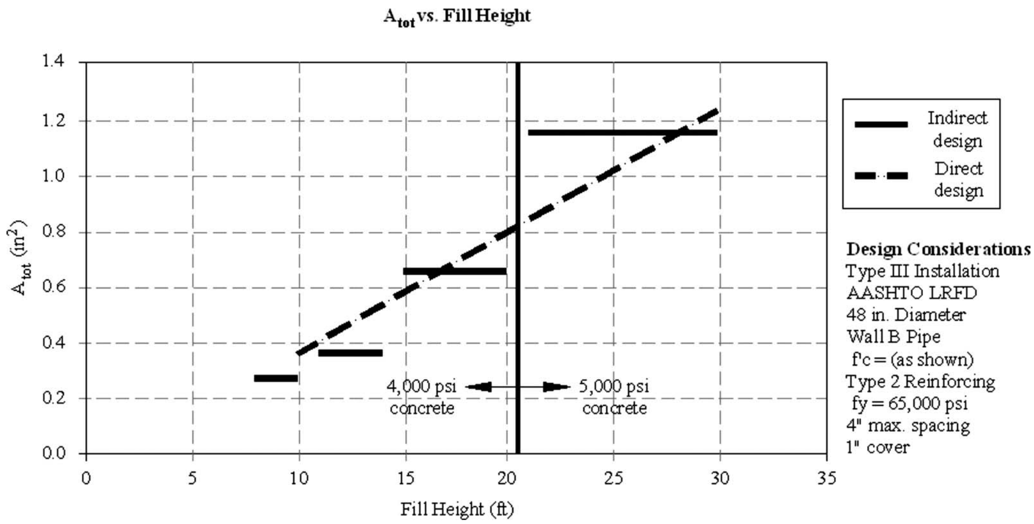

Fig. 7. Comparison of indirect and direct designs (B. Skourup)

structures. The soil-structure interaction analysis is based on a finite-element pipe-soil model which allows calculation of both loads acting on the pipe and the moments, thrusts, and shears at points in the pipe circumference. These pipe wall forces are then used to determine reinforcing requirements for both ultimate limit states and crack control. The following steps outline the procedure for reinforcement design (ACPA 1993):

- Determine the amount of reinforcement required at both the inner and outer faces of the pipe wall governed by the tensile yield strength of the reinforcement.
- Check if maximum factored moments at the invert and crown combined with thrusts exceed the radial tension strength limit.
- Check if maximum factored moments at the invert, springline, or crown combined with thrusts exceed the compression strength limit.
- Check if critical shears in the pipe wall exceed the shear strength limit.
- If any strength limits require more reinforcing than provided by tensile yield of the reinforcement, the design is modified to satisfy each limit.
- Check if service load moments combined with thrusts at the invert, springline, or crown cause reinforcement stresses that exceed the service load limit for crack control.

The analysis and design of RCP by the direct design method is much more rigorous than the indirect design procedure. However, the use of computers to perform the calculations allows a designer to design pipe efficiently and accurately. The ASCE SIDD practice facilitates a rational design procedure for structural engineers, which makes it possible to design the most efficient concrete pipe-soil installations.

Comparison of Design Methods

In the state of Nebraska, Type 3 installations and 48-in. diameter pipe are commonly specified for buried concrete pipe. This example is used as a basis for comparison of the direct and indirect design methods. The installation type, design criteria, pipe diameter, wall thickness, and reinforcing type are held constant. Pipe designs, in terms of reinforcing steel required, are computed using both methods for fill heights varying from less than 10–30 ft.

The ACPA fill height tables are design aids published to facilitate the use of the indirect design method incorporating standard installations and are used here to select a pipe class based on the installation type, pipe diameter, and fill height. After the required *D* load is identified, the reinforcing steel areas and the concrete strength for the appropriate pipe are selected from those specified in ASTM C76 (ASTM 2005).

The software PipeCAR (ACPA 2002), which facilitates the direct design procedure, is used to design reinforcement for pipe with the same installation type, concrete strength, and reinforcement yield strength as pipe that are specified by ASTM C76. This is done to provide a comparison that reveals the differences in the resulting reinforcing steel areas based solely on the design method.

Fig. 7 presents the results of the comparison between pipes designed using the indirect design method and the direct design method. The following observations can be made from this comparison:

- Sometimes the indirect design method is more conservative, sometimes it is less conservative, and therefore a general statement of conservatism between both methods cannot and should not be made. For example, the indirect design for 25 ft of fill requires more reinforcing than the direct design for the same fill height. However, the indirect design for 30 ft of fill requires less reinforcing than the direct design for the same fill height. Note that the area of reinforcing for both fill heights is constant for pipe designed by the indirect design method.
- The direct design method always provides a unique and conservative design for each specific pipe installation while the indirect design procedure is a more generalized approach to the design of buried pipe. The area of reinforcing steel required by the direct design method is a function of fill height, whereas the area of reinforcing steel required by the indirect design method is based on empirical data and does not vary linearly with fill height.
- The direct design method checks limit states while the indirect design method is based on empirical evaluation. However, these empirical methods may not be appropriate in cases where the limit states in TEB tests and field installations are different.
- The direct design method generates steel reinforcing that is appropriate to installation-specific characteristics. The indirect design method may require more or less steel than the direct

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design method depending on installation characteristics. Therefore, the direct design method is more efficient and flexible with respect to use of reinforcing steel.

Moreover, the direct design method has various advantages over the indirect design method, as listed in the following (ACPA 1993):

- Efficient use of outer cage reinforcing in contrast to empirical requirements for outer cage reinforcing specified in ASTM C76 (ASTM 2005).
- Development of a rational method to determine when shear reinforcing is required.
- Variable material strengths and crack control characteristics are accounted for in the direct design method.

Conclusions

It is anticipated that designers may choose to continue using the indirect design method for the specification of RCP. The indirect design method requires fewer steps to perform design than the direct design method, thus presenting the advantage of ease in use. However, additional assumptions are implicit in indirect design due to the simplification of the problem. Inconsistent margins of safety for design can result if these implicit assumptions are not well understood. The relationship of pipe limit states in a TEB test and the installed condition may not reflect the relationship implied by the bedding factor. Therefore, the supporting strength of the pipe calculated using the bedding factor is inconsistent with the actual behavior of the pipe. The benefit of axial compression due to lateral soil pressure acting on the pipe may be overstated in the latest formulation of the bedding factor. An unwarranted increase in axial compression may understate the required supporting strength of the pipe. Due to the empirical nature of indirect design specifications, steel reinforcement is not used efficiently. Indirect design of RCP will result in more or less steel than that required by the direct design method resulting in additional capacity for some cases and lesser capacity in others. If the designer chooses to use the indirect design method, the writers recommend the use of standard installations for their constructability and economy. The results of indirect design of RCP using standard installations correlate better with the results generated by the direct design method.

The direct design method is a more flexible, modern, theoretical, and sophisticated practice for the design and installation of RCP taking into account all of the important factors that affect RCP behavior. Direct design methods use modern concepts of reinforced concrete, a limit states approach, to provide economic and conservative design for a wide variety of installation characteristics. The direct design method provides flexibility in the selection of material strengths, and uses reinforcing more efficiently than the arbitrary rules that govern indirect design reinforcing. For these reasons, the writers conclude that the direct design method is a superior method for the design of buried RCP installations.

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Notation

The following symbols are used in this paper:

a = depth of equivalent compressive stress block (mm);
B_f = bedding factor;
B_{fe} = bedding factor, embankment condition;
B_{ft} = bedding factor, trench condition;
c = concrete cover over the inner reinforcement (mm);
D = internal pipe diameter (mm);
FS = factor of safety;
h = pipe wall thickness (mm);
M_A = invert moment under TEB load;
M_E = effective moment $[(\mathrm{N\cdot mm})/\mathrm{m}]$;
M_{FI} = invert moment in the installed condition $[(\mathrm{N\cdot mm})/\mathrm{m}]$;
M_{field} = invert moment in the installed condition including axial thrust $[(\mathrm{N\cdot mm})/\mathrm{m}]$;
M_{test} = invert moment in the TEB test $[(\mathrm{N\cdot mm})/\mathrm{m}]$;
M_U = ultimate moment $[(\mathrm{N\cdot mm})/\mathrm{m}]$;
N = constant depending on distribution of vertical loading and vertical reaction;
N_{FI} = invert axial thrust in the installed condition (N/m);
N_{FS} = springline axial thrust in the TEB test (N/m);
N_U = ultimate axial thrust (N/m);
P = TEB load;
q = ratio of total lateral pressure to total vertical pressure;
R = mean radius of the pipe section;
t = pipe wall thickness (mm);
TEB = test load (N/m);
W = total load (kg/m); and
x = function of distribution of lateral pressure.

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