BURIED facts

STRUCTURAL DESIGN CONSIDERATIONS

Liberal policies for corrugated steel pipe are sometimes promoted which are not equal to the generally more stringent requirements for concrete pipe. When the various design methods and criteria developed for the different materials available for sewers and culverts are considered, policy decision procedures can become exceedingly complex.

Satisfactory design methods must be based on theories, model and full-scale testing, and, most importantly, experience. Appropriate criteria involves relating requirements for usage and performance with experience. Pipe policies generally have certain political and economic overtones, but they should also be based on experience.

The proper design of sewers and culverts requires consideration of the different, but interrelated, fields of hydrology, hydraulics, structural behavior, durability and economics, and construction procedures. Knowledge of the performance of a pipe material in each of these fields is essential for complete evaluation and comparison. This *Buried Fact* reviews the structural behavior of flexible corrugated steel pipe and the development of design criteria and procedures.

Sewers and culverts must have adequate structural strength to withstand external loading from construction equipment, earth backfill and traffic, and must maintain structural integrity for the design service life. The load carrying capability of any pipe is dependent upon the inherent structural strength of the pipe and the support provided by the surrounding soil.

Concrete pipe can be designed with the strength necessary to carry practically any load, and designs are based on proven and universally accepted principles of engineering mechanics. Concrete pipe can be tested, and its structural strength proven before purchase and installation.

Corrugated steel pipe is a thin, flexible structure. It has virtually no inherent strength to resist external loads and handling stresses. Its supporting strength depends on more stringent and difficult requirements for foundation preparation, bedding preparation, pipe handling and placement, backfill material and fill procedures. Values for all of these requirements must be assumed during the design phase, and structural distress or failure may result when a design value is not achieved during installation. Because of flexibility and lack of inherent structural strength, corrugated steel pipe failures occur as a result of deflection, buckling of the pipe wall, splitting of the pipe wall seams, damage during installation, and other installation problems including flotation due to light weight. This light weight and lack of inherent structural strength are directly related to the very thin wall thickness of corrugated steel pipe.

For most pipe sizes, more steel is used in reinforced concrete pipe than is used for corrugated steel pipe. For example, as shown in *Table 1*, a 60-inch diameter rein-

Table 1. Comparison—Concrete Pipe vs. CSP.

PIPE DIAMETER, INCHES	WALL THICKNESS, INCHES		STEEL USAGE, POUNDS PER LINEAR FOOT	
	CONCRETE PIPE	CSP	CONCRETE PIPE	CSP
36	4	0.064	36	33
48	5	0.064	67	44
60	6	0.079	108	67
72	7	0.109	125	110
84	8	0.109	181	128
96	9	0.079	221	147

NOTES: *1. Concrete pipe—Wall B, Ohio DOT Design Tables*
2. CSP—3 x 1 corrugations

forced concrete pipe has 61 percent more steel than a 60-inch diameter, 14-gage corrugated steel pipe. In addition, the steel in concrete pipe is covered with dense, protective concrete.

DESIGN

A flexible corrugated steel pipe has virtually no inherent flexural strength, and, in the buried condition, its ability to support vertical loads must be derived from active lateral pressures and passive lateral pressures of the soil induced as the pipe deflects and its sides move outward. Since the pipe supporting strength depends on the sidefill material, its structural behavior must be analyzed considering soil-structure interaction which is directly related to deflection changes of the pipe. Any rational structural design procedure for buried flexible pipe should include a method for predicting deflection under specific installation conditions so as to prevent buckling and inverse curvature of the pipe.

In the design of structural members, the strain or deformation of an element can be determined from the ratio of the load or stress on the member to its modulus of elasticity (strain = stress ÷ modulus of elasticity). The modulus of elasticity for the material is either known or it can be determined from laboratory tests.

The deflection of a buried circular pipe can be predicted in a similar fashion. The cross-sectional ring deflects (deforms) according to the ratio of the load on the ring to the modulus of elasticity of the material. In this instance, the material modulus is a combination of the structural modulus (stiffness) of the pipe and the modulus (stiffness) of the soil, so that:

$$\text{pipe deflection} = \frac{\text{load on pipe}}{\text{pipe stiffness} + \text{soil stiffness}}$$

This is the form of the Iowa Formula, widely used for predicting deflections of buried corrugated steel pipe.

IOWA FORMULA

Professor M. G. Spangler, Iowa State University, published the Iowa Formula in 1941:

$$\Delta X = \frac{D_{\ell} K W R^3}{EI + 0.061 e R^4}$$

where:

ΔX = horizontal deflection of the pipe, inches
D_{ℓ} = deflection lag factor
K = bedding constant which varies with the angle of the bedding
W = earth load on the pipe, pounds per linear inch
R = mean pipe radius, inches
E = modulus of elasticity of the pipe material, pounds per square inch
I = moment of inertia of the pipe cross-section, inches to the fourth power
e = modulus of passive resistance, pounds per square inch per inch

Professor Spangler developed the formula from experimental installations of buried flexible corrugated steel pipe. A total of ten pipe were tested with diameters ranging from 36 inches to 60 inches, under a uniform height of fill of 15 feet.

Spangler hypothesized that if the lateral movement of various points on the pipe ring were known, the distribution of lateral pressures could be determined by multiplying the movement of any point by the modulus of passive resistance, e. For mathematical convenience, this lateral pressure was assumed to be a simple parabolic curve embracing only the middle 100 degree arc of the pipe, *Figure 1*. He also assumed the total vertical load was uniformly distributed across the width of the pipe, and the bottom vertical reaction, equal to the vertical load, was distributed uniformly over the width of the pipe bedding.

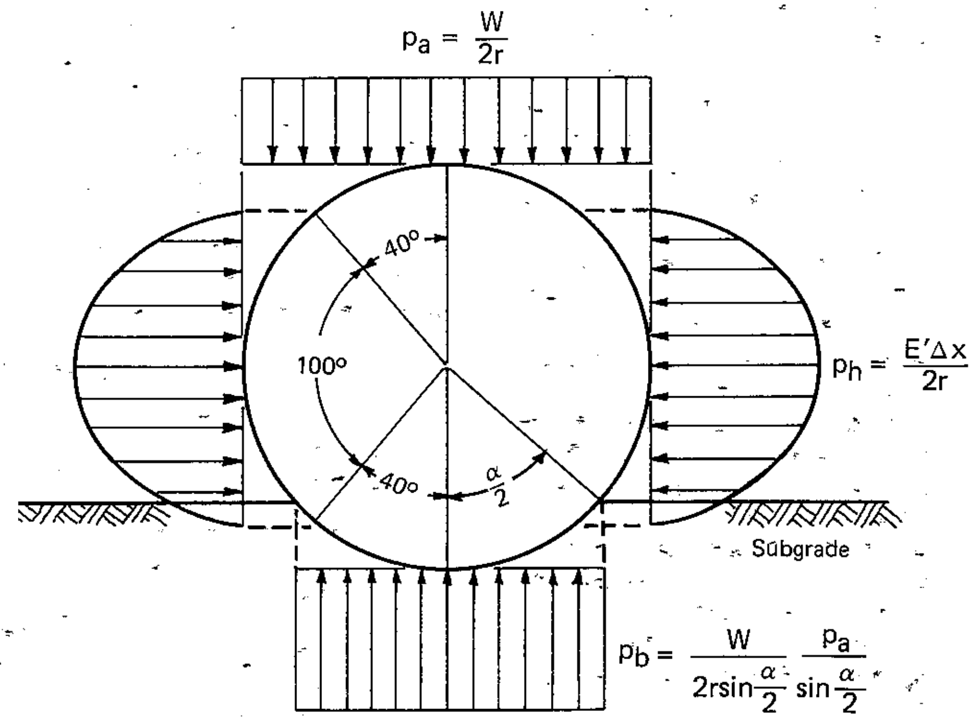

Figure 1. Spangler Assumptions for Pressure Distribution.

The Marston load theory was used to evaluate the total vertical load, W, on the pipe:

$$W = CwB_c^2$$

where:

C = load coefficient
w = weight of backfill material, pounds per cubic foot
B_c = outside width of pipe, feet

The load coefficient varies with the type of backfill material and depth of burial, and, in the embankment condition, is also affected by the projection ratio and the settlement ratio. The settlement ratio is a rational concept, but impossible to evaluate in advance of construction, and, therefore, is considered a semi-empirical constant. Recommended values for the settlement ratio were determined from a very small number of flexible pipe installations.

In 1955, after discovering that the modulus of passive resistance could not possibly be a property of soil because its dimensions were not those of a true modulus, Spangler and Dr. R. K. Watkins proposed a modulus of soil reaction, E′, defined as:

$$E' = eR$$

The modified Iowa Formula, as used today, is therefore:

$$\Delta X = \frac{D_\ell KWR^3}{EI + 0.061\,E'\,R^3}$$

If the Iowa Formula is rearranged as:

$$\Delta X = \frac{(D_\ell KW)}{(EI/R^3) + (0.061\,E')}$$

The following terms can be introduced to describe the three separate factors that affect the pipe deflection:

D_1KW = load factor
EI/R^3 = ring stiffness factor
$0.061\,E'$ = soil stiffness factor

And the modified Iowa Formula represented as:

$$\Delta X = \frac{\text{Load Factor}}{\text{Ring Stiffness Factor} + \text{Soil Stiffness Factor}}$$

LOAD FACTOR

The load factor incorporates the parameters that have to do with the magnitude and distribution of the soil pressures on a buried pipe. The pipe deflection is directly proportional to the load factor and, yet, less is known about its components than any others in the Iowa Formula. Changes in construction procedures or bedding could vary the actual load factor more than 100 percent from the load factor calculated in the design phase.

Deflection Lag Factor

Spangler originally stated, "The deflection lag factors observed in the experiments range from 1.38 to 1.46, and in no instance was equilibrium completely attained. Therefore, 1.5 is suggested as a conservative value for design use for standard corrugated-pipe culverts installed without strutting or predeforming," and after further investigation, "The deflection lag factor cannot be less than unity and has been observed to range upward toward a value of 2.0. A normal range of values from 1.25 to 1.50 is suggested for design purposes." The U. S. Bureau of Reclamation, however, after review of many projects, concluded that, "The actual value, however, depends on when the immediate deflection is measured, the volume change rate of the soil, and the load on the soil. D_ℓ is basically an empirical factor and ranges from 1 to 6 in observed tests."

Bedding Constant

The bedding constant, K, is dimensionless, and varies with the bedding angle, α *(Figure 1)*, as presented in *Table 2*. The angle of bedding describes the load resisting area of the bedding under the pipe. As the angle of bedding increases, the loaded area increases and the pipe deflects less. No further study has been done on this constant since its conception in 1941, even though it can influence the deflection predicted by the Iowa Formula by as much as 25 percent.

Earth Load

The Marston theory is the most common method of calculating the earth load, W, on the pipe and is recommended by Spangler for the Iowa Formula. In the Marston theory, the load depends on whether the pipe is in a trench or embankment (or combination), the type of backfill soil, the settlement of the pipe in relation to the backfill material, and the distance that the pipe projects into the natural soil foundation. Virtually all corrugated steel pipe research and experience has been on highway culverts constructed as positive projection embankment installations, where good side fill compaction is relatively easy to achieve. Conversely, there is a lack of research and experience on corrugated steel pipe installed in trench conditions.

Table 2. Bedding Angle—Constant Relationships.

BEDDING ANGLE, α	BEDDING CONSTANT, K
0°	0.110
30°	0.108
60°	0.102
90°	0.096
120°	0.090
180°	0.083

RING STIFFNESS FACTOR

The ring stiffness factor, EI/R^3, is the product of the modulus of elasticity of the pipe wall material and the moment of inertia of a one-inch length of pipe divided by the pipe radius cubed. The EI value may be found using approximate values for E and I or EI can be determined by conducting three-edge bearing tests on a section of pipe. During the test, deflections due to line loads on the top and bottom of the pipe are measured and EI calculated from either:

$$EI = 0.149 \frac{PR^3}{\Delta Y}$$

or

$$EI = 0.136 \frac{PR^3}{\Delta X}$$

where:

P = three-edge bearing test load, pound per linear inch
R = mean pipe radius, inches
ΔX = horizontal deflection, inches
ΔY = vertical deflection, inches.

In the three-edge bearing test, the pipe deforms ellipitically with the horizontal deflection theoretically about 91 percent of the vertical deflection.

SOIL STIFFNESS FACTOR

The only variable in the soil stiffness factor, 0.061 E′, is E′. A constant E′ of 700 was originally suggested for soils placed at over 90 percent laboratory maximum dry density. Spangler, however, regards E′ as a semi-empirical constant, and has stated, "The properties of the soil which influence this factor are somewhat obscure although qualitatively it is certain that texture and density characteristics are of prime importance. Probably moisture content is also influential."

Several investigators have attempted to determine E′ by direct laboratory measurements, but without success. Recently, several investigators have attempted to correlate E′ with basic soil properties, but these correlations have not yet been widely tested.

Only 18 full-scale field test installations have been fully instrumented and documented in the development of structural design criteria for corrugated steel pipe. Analysis of the results of these tests indicates completely unreliable confidence levels, *Table 3*, and that the E′ varies over a very wide range, from as little as 200 psi to as much as 8,000 psi, a 40-fold variation.

The U. S. Bureau of Reclamation analyzed available data from over 100 projects which included various pipe materials, pipe diameters, backfill depths, and installation conditions, and published backcalculated values of E′, *Table 4*, which were related to the pipe bedding material and the degree of compaction. The recommended values of E′ range from 50 to 3,000, and were verified by laboratory tests. The Bureau of Reclamation, however, cautions that unless the degree of compaction is greater than 95 percent Proctor, the actual defection can vary from predicted values by as much as 2 percentage points.

CORRUGATED STEEL PIPE INDUSTRY

Although Spangler and other researchers conclude that caution and more conservatism are advisable, the corrugated steel pipe industry has promoted drastically liberalized design criteria over the last 20 years. For example, the height of cover over a 14-gage, 48-inch diameter corrugated steel pipe, with 2⅔ by ½ inch corrugations, was promoted as a maximum of 6.9 feet in 1958... 10 feet in 1966... 37 feet in 1970... and has been proposed as a maximum of 120 feet in a 1970 research report. These fill height changes are based solely on theory and model testing, and have caused controversy in the research and design professions.

The Federal Highway Administration 1970 publication, "Corrugated Metal Pipe, Structural Design Criteria and Recommended Installation Practice," states in the foreword: "The most radical change in this publication is the increased values for allowable fill heights as a result of the change in the design value of soil modulus E′ from 700 to 1400 psi." It is interesting to note this radical doubling of the value of the soil modulus admittedly was not based on any full-scale research, new innovative technology, or

Table 3. CMP Field Test Data.

TEST GROUP NO.	NO. OF SPECIMENS	H FT.	(H/B_c) AVG.	e		E′	
				MEAN	STD. DEV.	MEAN	STD. DEV.
I	10	15	4.09	21	7.5	471	182
II	5	12	5.65	56	23	734	326
III	1	137	19.60	190	–	7980	–
IV	1	170	30.90	40	–	1320	–
V	1	83	4.60	58	–	6300	–
Total	18		6.90	43	41	1332	2094

Table 4. Values of E′ for Initial Flexible Pipe Deflection.

Soil type-pipe bedding material (Unified Classification System)[1]	E′ for degree of compaction of bedding (lb/in²)			
	Dumped	Slight <85% Proctor <40% relative density	Moderate 85-95% Proctor 40-70% relative density	High >95% Proctor >70% relative density
Fine grained soils (LL > 50)[2] Soils with medium to high plasticity CH, MH, CH-MH	No data available; consult a competent soils engineer; otherwise use $E' = 0$			
Fine-grained soils (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with less than 25 percent coarse-grained particles	50	200	400	1000
Fine-grained soils (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with more than 25 percent coarse-grained particles *Coarse-grained soils with fines* GM, GC, SM, SC[3] contains more than 12 percent fines	100	400	1000	2000
Coarse-grained soils with little or no fines GW, GP, SW, SP[3] contains less than 12 percent fines	200	1000	2000	3000
Crushed rock	1000	3000		
Accuracy in terms of percent deflection[4]	±2%	±2%	±1%	±0.5%

1 ASTM Designation D 2487, USBR Designation E-3.
2 LL = liquid limit.
3 Or any borderline soil beginning with one of these symbols (i.e., GM-GC, GC-SC).
4 For ±1 percent accuracy and predicted deflection of 3 percent, actual deflection would be between 2 percent and 4 percent.

Note: A. Values applicable only for fills less than 50 ft.

B. Table does not include any safety factor.

C. For use in predicting initial deflections only, appropriate deflection lag factor must be applied for long-term deflections.

D. If bedding falls on the borderline between two compaction categories, select lower E' value or average the two values.

E. Percent Proctor based on laboratory maximum dry density from test standards using about 12,500 ft-lb/ft³ (ASTM D-698, AASHTO T-99, USBR Designation E-11).

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even satisfactory structural performance of corrugated steel pipe, but solely on theory and model testing.

The corrugated steel pipe industry is now promoting simplified design methods which further reduce wall thickness and the degree of soil compaction required, even though many installations designed with more conservative methods have failed. Another objective of this promotional effort is to eliminate deflection as a design criteria. Deflection will always be a governing factor in most designs, is a concern during the construction phase, and is critical to service performance. The Bureau of Reclamation concludes from its flexible pipe research that a final deflection of more than 3 to 4 percent can result in failure of pipe or its coating or lining.

RECOMMENDATIONS

Long life, with minor maintenance, is an important requirement for a value engineered pipe project. Concrete pipe satisfies this requirement with the added benefits of being hydraulically efficient, noncombustible, corrosion resistant, construction adaptable, and structurally rigid and self supporting.

Results of numerous independent and impartial investigations present clear evidence of potential problems with corrugated steel pipe. These problems are related to the variables and assumptions which must be made in the structural design, and the dependency on proper construction procedures to develop the load carrying capability of corrugated steel pipe. To alleviate problems and insure a structurally adequate installation requires use of conservative design values for the parameters in the deflection formula, and, during construction, use of select bedding and backfill materials, frequent inspections, more soil compaction tests, and pipe deflection testing.

If alternate bids must be specified, the concepts of value engineering should be applied, and an effective least cost analysis required to determine the most economical pipe material.

PIPE MATERIAL SELECTION

Selecting pipe materials best suited for service as a storm sewer, culvert, sanitary sewer, or small bridge replacement is of primary importance to the design engineer. Selection is based on hydraulic efficiency, structural integrity, durability and cost. On many projects when alternate materials are bid, selection is too often based on first cost. However, the alternate with the lowest first cost may not be the most economical selection for the design life of the project. The most economical alternate must be determined through a least cost analysis.

First cost of a pipe material is important to the engineer and owner, but does not reveal the entire cost of the pipeline. If the service life of an alternate material is less than the project design life, future replacement costs must be considered. If the service life of an alternate material is greater than the project design life, residual value at the end of the project design life must be considered. Future replacement costs involve assumptions about inflation and interest rates. High and fluctuating inflation and interest rates have been with us for some time, and assumptions about their magnitude 25, 50, or 100 years hence are merely guesswork. Buried Fact No. 4, "Bid Evaluation By Least Cost Analysis", presents a method of least cost analysis designed to eliminate the least reliable aspects of the assumptions necessary to compare the effective costs of the alternative materials.

The factors involved in a least cost analysis are:

- Project design life
- Material life
- First cost
- Interest rate
- Inflation rate
- Replacement costs
- Residual value

While most agencies expect roadways to last a certain number of years, and embankments indefinitely, incidental construction, such as culvert and sewer pipe, are often specified with little regard for durability. Buried Fact No. 4 presents guidelines for selection of an appropriate project design life for all pipe projects.

Major specifying agencies, such as the Federal Highway Administration, Corps of Engineers, Soil Conservation Service, and most state departments of transportation have published reports on field and laboratory investigations to determine the durability of pipe materials and establish methods for predicting service life. An extremely important report for the engineering profession is the Ohio Department of Transportation publication "Culvert Durability Study." The report evaluates the durability performance of both concrete pipe and corrugated steel pipe under the same environmental conditions, and presents predictive equations and graphs for establishing service lives for both materials. Buried Fact No. 2, "Culvert Durability Study", reviews the Ohio Report and presents procedures for evaluating service lives.

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