Factors of Safety in the Design of Buried Pipelines

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This paper examines the facts and circumstances that should be considered in determining the factor of safety to be used in the design of several types of buried pipelines. Factors of safety based on yield strength or on ultimate strength of the pipe are defined and considered for reinforced concrete pipe, nonreinforced rigid pipes, and flexible metal pipes. Recommended factors of safety vary from 1.0 to 1.5, depending on the circumstances of construction, i. e., the type of pipe, bedding, knowledge of the character of the soil involved, permissible deflection, and the type of strength test used on the pipe.

•THE STRUCTURAL design of a buried pipeline follows the same sequence of operations as does the design of more conventional sturctures, such as bridges and buildings, and consists of two principal phases. First, it is necessary to determine the loads and pressures to which the pipeline will be subjected during its functional life. The second phase is to select the materials, proportion the pipe, and design the pipe installation, all so related that the structure will adequately support the maximum expected load system with a reasonable factor of safety.

Factor of safety may be broadly defined as the ratio of the maximum load that a structure is capable of supporting to the load that it is designed to carry. This ratio may be determined in a variety of ways. For example, in the case of a steel structure it may be expressed as the ratio of the yield strength of the material to the moment design stress. Thus the factor of safety based on yield is

$$FS = \frac{\text{yield strength}}{\text{design stress}} = \frac{33000}{20000} = 1.65$$

In this instance it is assumed that the load-supporting strength of the structure is proportional to the yield strength of the steel. Some designers may wish to consider the ultimate strength of the steel as the appropriate criterion of supporting strength, in which case

$$FS = \frac{\text{ultimate strength}}{\text{design stress}} = \frac{64000}{20000} = 3.2$$

Obviously it is necessary to specify the basis upon which the factor of safety is applicable in order to keep the meaning clear.

Factors of safety may also be applied to other phenomena in place of or in addition to moment design stress, such as shear, torsion, or deflection, depending on the importance of these criteria in relation to the maximum load the structure can carry. In some situations a factor of safety may be applied in the design of a structural element

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to protect an adjunct material, as in the case of a beam that supports a plastered ceiling. In this case the choice of a factor of safety depends on the deflection characteristics of the plaster material, and not on the strength or deflection capabilities of the beam itself.

The purpose of a factor of safety is to guard the completed structure against damage or failure caused by applied loads or circumstances that may be greater or more damaging than those that a skillful designer can logically predict. Or it may be needed to protect against possible shortcomings and inadequacies in the most modern and widely accepted design methods, or possibly against normal and unpredictable variations in strength of materials.

A factor of safety should not be used to mask or cover up sloppy design work, careless construction, inadequate or incompetent inspection, or any other element that can be controlled by competent and alert engineering practice. Several years ago the author sat with a committee attempting to formulate a recommendation for factor of safety in sewer design. Quite naturally there were differences of opinion. One sewer design engineer on the staff of a large city argued for a high factor of safety because, he said, when a design left his department it was turned over to the construction department and they often made changes in installation that might influence strength of the pipeline. Therefore a high factor of safety was needed to guard against such a possibility. What that city really needed was a reorganization of its engineering staff to insure effective cooperation and understanding between designers and constructors. The structural performance of a buried pipeline depends nearly as much on the environment in which it is installed and the manner of its installation as it does on the inherent strength of the pipe itself.

These brief references to the employment of factors of safety in the processes of structural design illustrate the fact that there is no single basis for the application of this important factor and no single value is applicable to all elements of a structure or to all structures in a given category.

The choice of a suitable factor of safety cannot be made by the application of principles of engineering mechanics. It is not possible to establish basic criteria and then proceed by mathematical analysis to an estimate of an appropriate value as is normally done in the classical structural design process. The selection can only be based on sound engineering judgment founded on experience and observation of the performance of similar structures in similar environments and having similar functions. In the exercise of this judgment the basic conflict between reasonable prudence and reasonable economy must be kept constantly in mind. If the selected value of safety factor is too high, the design is uneconomical and the structure costs more than it should. Conversely, if the safety factor is too low, the risk of failure may be too great and the design is decidedly imprudent or marginal. Perhaps nowhere in the field of engineering is the need to exercise good, sound judgment more necessary than in the selection of a prudent, yet economical, factor of safety.

In the field of buried pipeline design, it is necessary to estimate the earth load to which the structure will be subjected. The most convenient and the most widely used tool for this purpose is the Marston theory of loads on underground conduits (1, Ch. 24 and 25). This theory was first announced in 1913 and has since gained worldwide acceptance and use. It is theoretically sound and both experimental evidence and long years of experience indicate that it yields results that are dependable and on the conservative side. It is applicable to all heights of fill and to all types of conduits, regardless of shape and material of composition.

Pipelines under relatively shallow cover may be acted upon by surface traffic loads (1, Ch. 16) such as truck wheels and airplane and railway traffic, including impact. Loads from these sources are combined with the earth load to obtain the total design load on the structure. Such loads may be estimated by means of the Boussinesq theory of stress distribution in elastic solids of semi-infinite extent or half space. Although the Boussinesq theory was developed with reference to an idealized elastic, isotropic, homogeneous material, and although soil definitely does not comply with these specifications, experimental evidence indicates that the theory is a valuable guide for estimating safe design surface load effects on buried conduits. After extensive measurements of loads transmitted to a culvert under various depths of cover, the writer and colleagues (2) offer the following conclusion:

> The theoretical formula (Boussinesq) seems to give a locus showing the maximum possible percent of load transmitted through any thickness of fill. In the experimental work, however, this maximum load generally was not reached, but when conditions were most favorable,... the experimental results came very close to the theoretical.

The load-supporting strength of a buried pipeline is intimately dependent on the shape of the pipe and its component materials. In this connection, two general classes of pipes are recognized. These are rigid pipes, such as those manufactured of plain or reinforced concrete, burned clay, asbestos cement, or cast iron, and flexible pipes, such as those fabricated of corrugated steel, corrugated aluminum, smooth steel, ductile iron, or reinforced plastic mortar.

Speaking broadly, rigid pipes are those that deform very little under load and fail by rupture of the pipe wall. Before cracks develop in the wall, rigid pipes deform a negligible amount under load, and lateral pressures that may act against the sides are considered to be active lateral pressures. Flexible pipes, in contrast, are those that deform relatively large amounts and normally fail by excessive deflection. The sides of a flexible pipe as it deflects under vertical load move outward against the enveloping soil enough to mobilize passive resistance pressures, and these provide a major portion of the pipe's ability to carry the vertical load. Reinforced concrete pipes, which are normally rigid when loaded beyond their initial cracking stage, may gradually become essentially semiflexible in character as cracking progresses. As such, they may deform enough to mobilize the passive resistance property of the enveloping soil as the sides of the pipe move outward. Under these circumstances a substantial portion of supporting strength of the originally rigid structure gradually shifts from its inherent strength characteristics to dependence on the passive resistance of the sidefill soil.

REINFORCED CONCRETE PIPE

Reinforced concrete pipes, widely used in sewer and culvert construction, obviously fall in the rigid pipe category. Their supporting strength in a field installation depends on three major factors: the inherent strength of the pipe, the quality of the pipe bedding as it affects the lateral distribution of the vertical reaction on the bottom of the pipe, and the magnitude and distribution of active lateral pressures acting against the sides of the pipe.

Inherent strength is the strength built into a pipe by the manufacturer. It depends on the wall thickness; the quality of the concrete; the kind, quality, and amount of steel reinforcement; and the placement of the steel. This matter of steel location is extremely important because pipe walls are relatively shallow elements and if the reinforcement is even slightly out of place the lever arm between the compression area and the tensile steel may be seriously modified. Some intangible factors that seem to influence inherent strength are the character of raw materials, the skill of the manufacturer, and quality control practices, including curing of the concrete, that are in effect at a production plant. Experience shows that pipes of exactly the same physical dimensions, made in different plants, may consistently vary in strength.

The inherent strength of rigid pipes is determined by the three-edge bearing laboratory test specified by the American Society for Testing and Materials (ASTM C 497). For reinforced concrete pipes, two separate and distinct criteria for measuring strength are specified. These are the load to produce a crack 0.01 in. wide and the ultimate or maximum load that the pipe can withstand. The three-edge bearing test is quite severe, consisting of a load and reaction concentrated along longitudinal elements at the top and bottom of the pipe, without the application of any lateral forces.

The load-carrying capacity of a pipe installed in the ground is almost always greater than its strength in the testing machine. This is because the loads and reactions are distributed over greater widths and because of the possibility of lateral pressures acting effectively against the sides of the pipe. The more favorable load distributions reduce the bending moment in a pipe wall in exactly the same way that a distributed load on a simple beam reduces the bending moment as compared with that caused by a concentrated load of the same magnitude. As a generalization, the earth load on top of a pipe in the ground is essentially uniformly distributed over the full width of the pipe, i. e., the outside horizontal diameter. The width over which the bottom vertical reaction is distributed depends on the quality and character of the bedding in which the pipe is installed and may vary from the highly detrimental situation represented by a circular pipe resting on a flat bed of strain-resistant material (Class D bedding) to the very high quality concrete cradle (Class A bedding).

Under favorable circumstances a pipe may be acted on by active lateral earth pressures. This is particularly true of projecting conduits or conduits under embankments. Lateral pressures tend to produce bending moments in the pipe wall that are opposite in direction to those produced by vertical loads. Therefore, every pound of lateral pressure that can reliably be brought to bear against the sides of a pipe increases its capacity to carry vertical load about one for one.

The ratio of the strength of a pipe under any stated load system to its strength in the three-edge bearing test is called the load factor. It furnishes a medium by which the strength of a pipe as installed in the ground can be evaluated in terms of its three-edge bearing test strength. Experimental and analytical procedures have been used to evaluate load factors for a number of commonly specified types of bedding, both with and without lateral pressures on the sides of the pipes (3).

Load factors usually vary between 1.1 for Class D or impermissible bedding to well over 3.0 for Class A concrete cradle bedding. A special case worthy of note is that of bell and spigot pipes. The seat of strength of this type of pipe lies in the barrel, and it should be installed so that all of the bottom reaction impinges on the barrel with none acting on the bell. Some recent experiments by a private research agency have indicated that the load factor for pipes that rest heavily on the bells may be as low as 0.5 to 0.75. That is to say, pipes bedded in this manner may fail under loads that are less than the three-edge bearing strength of the pipes. This indicates very strongly that bell holes should be provided when bell and spigot pipes are installed. These should be deep enough and wide enough to insure that all of the bottom reaction acts only on the pipe barrel.

An example of the design of a reinforced concrete pipe culvert is given to illustrate the application or determination of the safety factor. Consider a 60-in. pipe under 43 ft of fill with the pipe installed on a Class B bedding and by the imperfect ditch method of construction (1). Assumptions: $H = 43$ ft, $B_c = 6$ ft, $w = 120$ pcf, $p' = 1.0$, $r_{sd} = -0.5$, $K\mu = 0.13$.

Load calculation:

$$\frac{H}{B_c} = \frac{43}{6} = 7.17$$

$$C_n = 4.3$$

$$W_c = 4.3 \times 120 \times 6^2 = 18600 \text{ plf}$$

Strength calculation: Assume $m = 0.7$, $K = 0.33$, $N = 0.707$, $x = 0.595$;

$$q = \frac{0.7 \times 0.33}{4.3} (7.17 + 0.35) = 0.404$$

$$L_f = \frac{1.41}{0.707 - (0.594 \times 0.404)} = 3.02$$

Required 3-edge bearing strength:

$$\frac{18600}{3.02} = 6160 \text{ plf}$$

Required D-load strength:

$$\frac{6160}{5} = 1230 \text{ D}$$

Using ASTM C 76 Class III pipe, minimum D-load strength at 0.01-in. crack = 1350 D. Therefore, the factor of safety based on the minimum 0.01-in. crack strength is

$$\frac{1350}{1230} = 1.1$$

These calculations indicate that the factor of safety of this pipe installation will be 1.1 based on the minimum 0.01-in. crack strength of the pipe.

It is this writer's judgment that a factor of safety of 1.0 is a prudent, economical minimum value for use in the design of a reinforced concrete pipe installation when the design is based on the specified minimum 0.01-in. crack strength of the pipe. Reasons for this belief are as follows:

1. The failure of this type of structure does not involve the safety of human life;
2. The specified strengths of pipes at 0.01-in. crack are minimum values and the great bulk of pipes in a given class will have strengths greater than the value specified;
3. Reinforced concrete pipes have a large reservoir of load-carrying capacity beyond the 0.01-in. crack stage due to inherent strength and the strength imparted by passive soil pressures as the pipe deforms; and
4. A pipe in the ground does not fail suddenly or collapse completely, so there is adequate time for making repairs in case of accidental overloading.

The application of a factor of safety of unity, based on the minimum 0.01-in. crack test load, suggests the possibility that if all the factors influencing load and supporting strength operate at their assumed or calculated values, a small number of individual pipe sections in a pipeline will develop longitudinal cracks that are 0.01 in. or less in width. Such cracks are not considered detrimental to the structural integrity of the pipe and certainly should not be regarded as a failure situation. Ordinary reinforced concrete (not prestressed concrete) is expected to crack, and all standard equations for calculating stresses in reinforced concrete beams assume that the concrete in the tensile zone is cracked. Unless a crack in the protective cover of concrete is sufficiently wide to permit corrosion of the steel, it is harmless. It indicates nothing more than that the steel is being stressed as expected, and because the modulus of elasticity of concrete is very much less than that of steel, the concrete does not stretch with the reinforcement but develops cracks instead. Also, a crack 0.01 in. wide at the surface of the pipe wall may be only about two-thirds as wide, or roughly 0.007 in., at the reinforcement because of the requirement for a minimum protective covering over the steel.

Some engineers prefer to apply a factor of safety to the ultimate test strength of the pipe rather than the 0.01-in. crack strength. The ASCE Manual of Practice No. 37, "Design and Construction of Sanitary and Storm Sewers," (WPCF Manual No. 9), recommends using a factor of safety of 1.5 based on the ultimate test strength of reinforced concrete pipe. It is noted that this value gives exactly the same result as the value of 1.0 based on the 0.01 in. crack strength in the case of ASTM C 76 Classes I, II, III, and IV pipe, since the required ultimate strength for these classes is 1.5 times the crack strength. For Class V pipe, the required test strengths are 3750 D at ultimate and 3000 D at 0.01-in. crack. Therefore, a factor of safety of 1.5 based on ultimate strength is the equivalent of 1.2 based on the 0.01-in. crack strength. However, since the ultimate test strength of a reinforced concrete pipe has no equivalent or comparable counterpart when the pipe is installed in the ground, because of the development of lateral passive resistance pressures by the enveloping soil as a cracked pipe deflects, factors of safety based on ultimate test strength have no numerical meaning, in this writer's opinion (4). In the foregoing example, the minimum required ultimate three-edge bearing strength of Class III pipe is 2000 D. Therefore the factor of safety based on ultimate strength is

$$FS = \frac{2000}{1230} = 1.63$$

compared with the value 1.1 based on the 0.01-in. crack.

NONREINFORCED RIGID PIPES

The inherent strength of nonreinforced rigid pipes is determined by the three-edge bearing test, the same as for reinforced concrete pipe, except that there is only one test load criterion—the ultimate strength. When a nonreinforced pipe cracks under test load it is finished, and the first crack strength and the ultimate strength are essentially the same. In the testing machine, pipes of this kind normally break into quadrants of approximately equal size and then collapse. When excessively loaded in the ground they also break into quadrants, but may or may not collapse immediately because of lateral support provided by soil at the sides. Broken pipes thus supported may continue to serve as conduits, sometimes for a fairly long period of time. However, eventually they may collapse as the supporting soil is eroded away by leakage, such as from a sewer operating under a head in time of excessive run-off, or other causes. Such broken pipes also contribute heavily to undesirable groundwater infiltration in sewer lines, which adds greatly to water pollution control and treatment costs. Certainly every effort should be made by a designer of this type of structure to guard against cracking of nonreinforced pipes.

Since there is no residual strength in a nonreinforced pipe, except what is ephemerally provided by soil at the sides, the factor of safety must be applied to the minimum ultimate test strength of the pipes to be used. A factor of safety of 1.5 is recommended, unless very favorable conditions relative to knowledge of local conditions that influence loads and strengths of pipe can be relied upon. The conditions referred to are precise knowledge of the character of the soil to be encountered, its unit weight and friction characteristics, an appreciation and understanding of the influence of high-quality bedding on the strength of pipes, a conscientious and knowledgeable contractor, and an organizational setup that insures competent and adequate inspection of the construction procedures. Under such favorable conditions the safety factor can prudently be reduced to 1.4 or even to 1.3 if conditions are exceptionally favorable.

FLEXIBLE METAL PIPES

Flexible metal pipes, fabricated of corrugated steel or aluminum, are widely used in drainage, irrigation, sewerage, and allied fields of construction. As indicated earlier, they tend to fail by excessive deflection. As they deflect under vertical load, the outward movement of the sides of the pipe is sufficient to mobilize the passive resistance pressure of the enveloping soil. This lateral pressure becomes an important source of supporting strength for this type of structure. A logical basis for design of flexible pipes is to estimate the probable deflection of the pipe and compare this with some established criterion for maximum allowable deflection. In addition, it is necessary to investigate the stress situation in longitudinal joints or seams of the pipe.

A widely accepted criterion is to permit a flexible pipe to deflect, i. e., the vertical diameter to shorten and the horizontal diameter to lengthen, an amount equal to 5 percent of its initial diameter. This percentage is based largely on observations made by the late George E. Shafer, formerly Chief Engineer of Armco Drainage and Metal Products, Inc. He measured diameter changes on a large number of corrugated steel culverts under fills of various heights and from these measurements concluded that such pipes can deflect up to approximately 20 percent of their initial diameter before failure by collapse is imminent. Therefore, he applied a safety factor of 4 and established an allowable deflection criterion of 5 percent. Shafer's data are unpublished and an independent appraisal of the validity of this criterion is not possible. However, the writer has observed a number of corrugated pipes in service and has seen nothing to negate his recommendation. Therefore, it is accepted, at least until more definitive research indicates a need for modification.

Measurements of radial pressures (5) around the periphery of a flexible culvert pipe clearly indicate that such pressures essentially are uniformly distributed and that they increase in magnitude as the height of fill increases. Some observers have interpreted these facts to mean that the only stress in a pipe wall is a circumferential or ring compressive stress, much the same as prevails if the pipe is acted upon by externally applied fluid pressure. However, each increment of fill load causes a corresponding increment of deflection, and this deflection brings about the equalization of external pressure, which makes it appear to be hydrostatic in character. Also, when a circular pipe deflects, there is bending moment in the pipe wall. Therefore the true stress situation in a flexible pipe wall is a combination of direct thrust and bending moment, not thrust alone.

These facts are important in connection with the design of longitudinal bolted seams in field-erected pipes, especially those of larger diameter. Pipe manufacturers have frequently designed bolted seams on the basis of single shear in the bolts or bearing of the plates on bolts, with a factor of safety said to be 3.5 to 4.0. Such designs may be inadequate because they do not take into account the bending moment at the location of the seam (6). This bending moment creates a prying action at the lapped seam, which causes direct tension in the bolts in addition to the direct shear stress.

The function of a longitudinal seam is to transmit both bending moment and shear (tangential thrust) from one ring plate to another. Unless the bolted seam is designed to transmit this composite stress situation, trouble may ensue, and the rather generous-sounding factor of safety based on direct shear alone may be misleading. There is need for extensive and detailed research to develop a more rational procedure for the design of longitudinal bolted seams.

SUMMARY

In summary, the writer recommends that a factor of safety of unity is both adequate and economical for reinforced concrete pipe installations designed on the basis of the minimum 0.01-in. crack three-edge bearing test strength of the pipe. If it is preferred to design on the basis of the ultimate test strength, a factor of safety of 1.5 should be used. For nonreinforced rigid pipes, a factor of safety of 1.5 based on the minimum ultimate test strength is recommended for general design application, with possible reduction to 1.4 or 1.3 in unusually favorable circumstances. In the case of flexible metal pipe installations, a limiting deflection of 5 percent of initial diameter is recommended. This is approximately one-fourth (factor of safety of 4) of a critical deflection of 20 percent. The design of longitudinal bolted seams in flexible metal pipes should be based on the ability of the seam to carry a composite of shear and bending moment stresses and not on shear strength alone.

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