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STRUCTURAL DESIGN PRACTICE OF PIPE CULVERTS

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•A DISCUSSION of culvert design practice must include methods of correlating design with actual construction procedures. Also pertinent are adaptations or extensions of the most widely used design procedures (including durability), which satisfy the practical needs of both the designer and the installation.

This paper discusses these items, and reference is made to the methods used by a large design and construction agency, the New York State Department of Transportation. Various aspects of the New York approach may be useful and can be adapted and utilized by any size organization if desired.

A great deal of research on culvert design has been done and is continuing. This paper suggests that the results of significant theoretical studies be reduced to practical terms so that they can be used routinely by all types of designers.

The structural design procedures of most organizations are based on the Marston-Spangler formulas for rigid pipe and on adaptations of the "ring compression theory" for flexible pipes. These methods have been thoroughly discussed, analyzed, and evaluated in innumerable studies and will not be repeated here.

The results of all evaluations, however, generally support the same conclusion—that current design procedures are satisfactory when properly applied. Proper application must, of course, include engineering judgment, provision for durability, and consistent, appropriate installation practices.

The most significant of the shortcomings commonly ascribed to the foregoing design methods are as follows:

1. Interactions of the soil-structure system are not properly considered;
2. Some of the input parameters are difficult to ascertain and must generally be assumed;
3. Results are usually conservative; and
4. Their applicability to extremely large structures under very shallow and extremely high fills is questionable.

Of all these criticisms, only the last one is not easily satisfied or provided for with a satisfactory degree of confidence in current design practice. It is reasonable to assume that the other shortcomings are sufficiently overcome such that practical results for routine installations are obtained. It is acknowledged, however, that the resultant safety factor for structural criteria is usually greater than required. The savings in cost that would accrue with the use of better-known formula input parameters with either existing or new design methods, however, would not always be especially significant for routine cases. For example, the minimum gauge of flexible pipe required to satisfy strength criteria after installation is often inadequate to also meet handling and durability requirements.

Durability is not included as an integral part of the structural design process for flexible structures. An initial attempt has been made in New York State to overcome this shortcoming and is described later.

The number of designs made each year by any large agency such as the New York State Department of Transportation is often staggering. Furthermore, design selections are made by perhaps hundreds of individuals within a state (or within a large design organization) who have limited expertise in soil mechanics and conduit structural

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analysis. Consequently, the need exists for designs and installation details to be standardized for the most commonly used shapes of rigid and flexible pipes for heights of cover up to about 100 ft. This concept is followed in varying degrees by many states. The approach used in New York is, therefore, not new in all respects but is believed to be quite comprehensive, easy to use, and successful in meeting the continuing challenge of designing large numbers of culverts.

The section that follows discusses this approach and the factors involved in establishing uniform design and installation standards. It should not be assumed from this presentation that current methods are considered to be entirely satisfactory or not in need of improvement or change. A case is being made, however, for the workability of current design methods when coordinated with construction practice and experience.

DESIGN APPROACH

The selection of a rigid or flexible pipe is not always made objectively. Sometimes it is based on the personal preference of the designer. The most recent procedure now being implemented in New York, however, is intended to be more objective; it is based on anticipated performance and cost. This design selection process first involves a determination of the required cross section for rigid and flexible pipes (including hydraulic factors). Structural analysis then follows, which must satisfy site requirements for fill height, foundation conditions, and durability considerations caused by the structure's environment.

This procedure often requires that a design cost analysis be made for both rigid and flexible pipes for many individual installations. Consequently, the desirability of easy-to-use standardized designs becomes even more apparent.

Rigid Pipe

In order to reduce the design process for routine conditions to its simplest form, i.e., a fill-height table, we first established a minimum number of practical installation conditions that cover all designs normally encountered in the field.

On New York State highway projects, for example, only two types of bedding are considered to be consistently attainable in the field when using reasonable procedures with varying qualities of inspection: class C or ordinary bedding and class A or concrete cradle bedding.

Only two design analysis loading conditions, positive projecting and imperfect trench, are routinely needed for each bedding condition to cover all methods of pipe installation commonly used on New York State projects. The positive projecting case covers the embankment installation as well as the trench and negative projecting conditions because the latter two types have been shown to require a trench width that is too wide for a trench or negative projecting loading. This minimum trench width is based on a 2-ft clearance between the pipe and the inside face of the trench plus the width of a sheeting section, which is always required for safety with trenches 5 ft or more in depth. Sheeting is seldom pulled incrementally as desired, and therefore the width of the sheeting section must be considered as a part of the trench width for load analysis. With the design analysis loading and bedding conditions thus established, the input parameters for the Marston-Spangler formulas can be selected or assumed as required.

In the approach followed by New York State for reinforced concrete pipe, a safety factor of 1 on the first crack strength and a soil unit weight of 125 pcf are used. The variation in settlement ratio and load factor has been shown to have a limited effect on the design results, providing reasonably representative constants are selected for these parameters. Height of fill-gauge tables for all field installation conditions such as embankment, trench (wide trench condition), and imperfect trench are therefore readily established by assuming values for settlement ratio and load factor and by making other appropriate inputs into the load analysis formulas. The designer, using these tables, needs only to select the "pipe strength-bedding type-installation method" combination that most economically satisfies the field condition. New York State's current allowable fill-height tables for reinforced concrete pipe are shown in Figure 1. It is noted that, in preparing these tables, design assumptions were modified and fill heights were

Figure 1. Fill-height design tables for reinforced concrete pipe.

INSTALLATION METHODS

Method D
(Imperfect Trench)

PIPE DIAMETER D (inches)	ORDINARY BEDDING 14R CLASS III	ORDINARY BEDDING 14 CLASS IV	ORDINARY BEDDING 14X CLASS V	CONCRETE CRADLE BEDDING 14R CLASS III	CONCRETE CRADLE BEDDING 14 CLASS IV	CONCRETE CRADLE BEDDING 14X CLASS V
	MAXIMUM HEIGHT OF FILL (H) IN FEET OVER TOP OF PIPE					
12	34	51	77	60	88	110
15	34	51	76	60	88	110
18	34	51	76	60	88	110
21	34	51	76	59	88	113
24	34	50	76	59	88	113
27	34	50	76	59	88	113
30	34	50	76	59	87	113
33	34	50	76	59	87	113
36	34	50	75	59	87	113
42	34	50	75	58	87	113
48	33	50	75	58	87	113
54	33	50	74	58	86	113
60	33	50	74	58	86	113
66	33	50	74	58	86	113
72	32	50	74	58	86	113
78	32	48	74	57	86	113
84	32	48	74	57	86	113
90	32	48	74	57	86	113
96	31	48	74	57	85	113
102	30	48	74	57	85	113
108	30	48	74	57	85	113
114	29	48	73	57	85	113
120	28	48	73	57	85	113
126	26	48	73	57	85	113
132	26	48	72	56	84	113
138	26	48	72	55	84	113
144	26	47	72	55	84	113

Method A (Sheeted Trench)
Method B (Open Excavation)
Methods C-1&C-2 (Embankment)

PIPE DIAMETER D (inches)	ORDINARY BEDDING 14N CLASS II	ORDINARY BEDDING 14R CLASS III	ORDINARY BEDDING 14 CLASS IV	ORDINARY BEDDING 14X CLASS V	CONCRETE CRADLE BEDDING 14N CLASS II	CONCRETE CRADLE BEDDING 14R CLASS III	CONCRETE CRADLE BEDDING 14 CLASS IV	CONCRETE CRADLE BEDDING 14X CLASS V
	MAXIMUM HEIGHT OF FILL (H) IN FEET OVER TOP OF PIPE							
12	9	13	19	28	18	24	35	54
15	9	13	19	28	18	24	35	54
18	9	13	19	28	18	24	35	54
21	9	13	19	28	18	24	35	54
24	9	13	19	28	18	24	35	54
27	10	13	19	28	18	24	35	54
30	10	13	19	28	18	24	35	54
33	10	13	19	28	18	24	35	54
36	10	13	19	28	18	24	35	54
42	10	13	19	28	18	24	35	54
48	10	13	19	28	18	24	35	54
54	10	13	19	28	18	24	35	54
60	10	13	19	28	18	24	35	54
66	11	13	19	28	18	24	35	54
72	11	14	19	28	18	24	35	54
78	11	14	19	28	18	24	35	54
84	11	14	19	28	18	24	35	54
90	11	15	19	28	18	24	35	54
96	11	15	19	28	17	24	35	54
102	11	15	20	28	17	24	35	54
108	11	15	20	28	17	24	35	54
114		15	21	28		24	35	54
120		15	21	28		24	35	54
126		15	21	28		24	35	54
132		16	21	28		24	35	54
138		16	21	28		24	35	54
144		16	22	29		24	35	54

Notes:

1. H-20 live loading effects are accounted for in the above tables with a minimum 2 ft. cover.

2. All design selections are field constructed in accordance with the corresponding Installation Methods and Bedding Details on the "Standard Drawing" except where modified by special requirements.

reduced where initially calculated allowable fill heights greatly exceeded 100 ft to ensure that these installations are given special consideration.

Although it is acknowledged that many excellent manuals (1) and guidelines exist for the application of the Marston-Spangler formulas, few if any are intended to be directly related to the actual construction practice of a given agency.

The key aspects involved in coordinating construction practice and design include standards for bedding, backfill materials, compaction requirements, minimum temporary cover and final cover, and construction procedures. Again, using New York State as an example, the coordination of construction and design is accomplished on a standard drawing that automatically becomes part of the plans and specifications whenever rigid pipe is used. Bedding details are shown that include additional procedures to be used by the field engineer in preparing the foundation. For example, rock foundations are required to be undercut below invert to as much as 75 percent of the pipe diameter, and temporarily unstable wet soil is replaced during the bedding process. Installation details are also shown for the trench and imperfect trench methods and two conditions of embankment installation: one for placing the pipe before filling and the other for building the fill to partial height and excavating a trench for pipe placement. All pipes after bedding, whether in cut or fill, are backfilled with a specified type of granular material placed to minimum established limits and compacted to between 95 and 100 percent of the maximum density as determined by AASHO T-99 Method C.

Durability design for rigid pipes must not be completely overlooked although it is not so significant a consideration as for flexible pipes. A brief but informative guideline on this subject for concrete pipe is given elsewhere (2).

Flexible Pipe

The most widely used design methods in current use are presented elsewhere (3, 4, 5). Each presentation is essentially the same and requires that the culvert be designed to meet seam strength, buckling, deflection, and flexibility criteria for the materials and corrugation configuration being used. Height-of-fill-gauge tables are given in some of the previously mentioned references, and similar ones have been prepared by many design agencies, which also incorporate their experience.

The most frequently discussed problem concerning the use of the design method is the inability to satisfactorily analyze the deflection aspect. This phase of the analysis relies largely on the determination or assumption of the modulus of soil reaction, E′, for use in the Iowa formula developed by Spangler. Various approaches for determining a reasonable value of E′ are summarized elsewhere (2). NCHRP Report 116 (2) should be referred to when a deflection estimate is of specific interest.

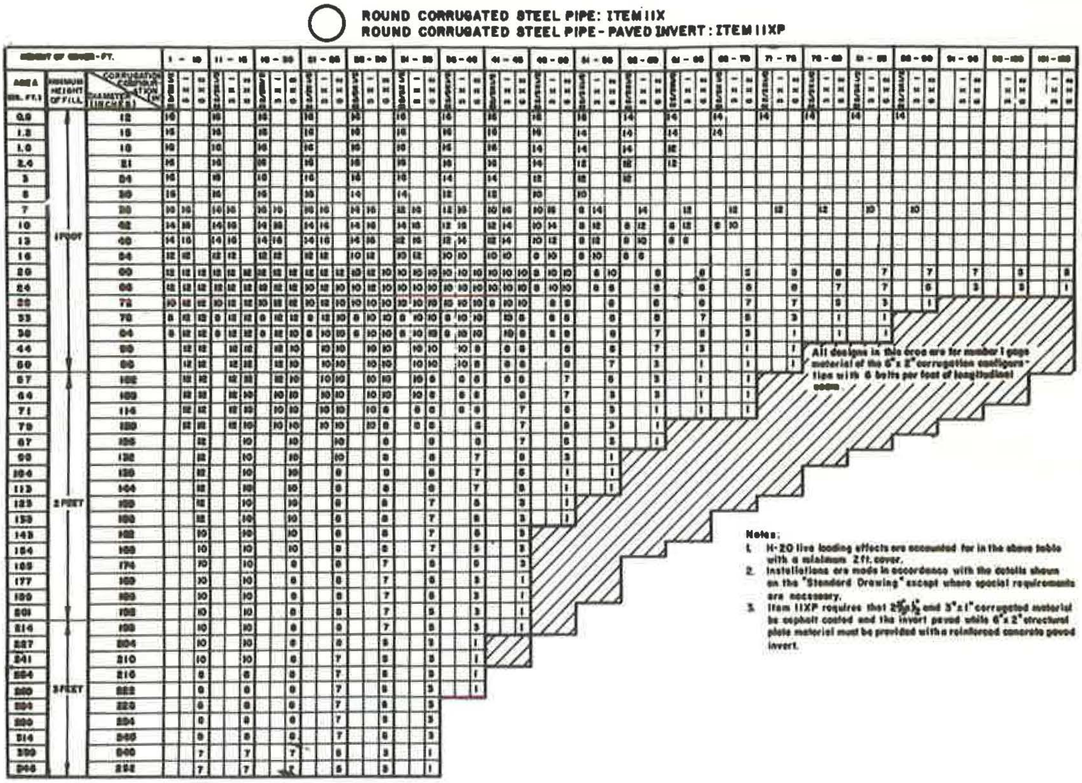
Extensive experience in New York highway work has shown that deflection of flexible pipes has been insignificant, i.e., generally much less than the usual arbitrary 5 percent criterion. This very favorable deflection performance is related to the compressibility of the surrounding backfill and therefore is attributable to the installation methods used. This has led to a recent decision to use round pipe exclusively for routine designs (except of course when pipe arches or other shapes are desired) and to eliminate elongation and strutting as a design consideration and construction requirement. This modified design approach will not result in any practical sacrifice to the value that E′ might attain if elongated pipe were to be used in place of round pipe. More economical designs should be realized although any resultant savings may not be reflected directly in a contractor's bid prices for this work.

The design for durability is not so easily accounted for as was deflection. Use of a New York State report (6) has been recommended for corrosion analysis. Durability design in New York, however, now includes considerations for abrasion, flow conditions, and service category as well as corrosion. In addition, the New York State corrosion study has been continuing, and based on more data, refinements, and new findings, the original report (6) is now used only as a reference for the corrosion part of durability design.

Attempts have been made to evaluate the corrosion aspect for a particular site by a series of field tests. Unfortunately, no completely satisfactory field test program has yet been developed that can be correlated to all of the factors that affect durability. New York State is currently initiating an interim qualitative approach to durability that relies on experience and past performance until more refined methods are developed.

Durability design for corrugated steel pipe (using the New York State method) provides for the use of plain galvanized material where feasible. It also requires, however, the coating and paving of inverts where indicated by using a rating system test applied to the proposed installation. Height-of-fill-gauge tables have been prepared for all corrugations of plain galvanized material by using the aforementioned design methods, but the tabulated gauges also contain an additional built-in consideration for durability. More specifically, each gauge that is listed must provide a minimum safety factor of 1 for seam strength and buckling at the end of a 40-year design life, assuming a uniform rate of metal loss over this period. The gauge table for round steel pipe is shown in Figure 2. Although the basis for durability assumptions is beyond the scope of this presentation, it may be of interest to know that rates of metal loss used were 1 mil per year for diameters up through 48 in. and 2 mils per year for larger sizes. These rates correspond to a statistical confidence level of about 85 percent. The remaining aspect of durability design for steel pipe requires that a determination be made for the need to completely asphalt coat and pave the invert of 2⅔- by ½-in. and 3- by 1-in. corrugated material or to install a reinforced concrete paved invert in structural plate (6- by 2-in.) pipes. It should be noted that experience in New York State has shown that asphalt coating alone is not significantly beneficial, and its single use is not recommeded. When a pipe with an asphalt coating and a paved invert or a reinforced concrete paved invert for plate is placed in an aggressive environment, the statistical rate of metal loss is equal to or lower than the rate for plain galvanized material in a nonaggressive environment.

Figure 2. Fill-height design table for round corrugated steel pipe.



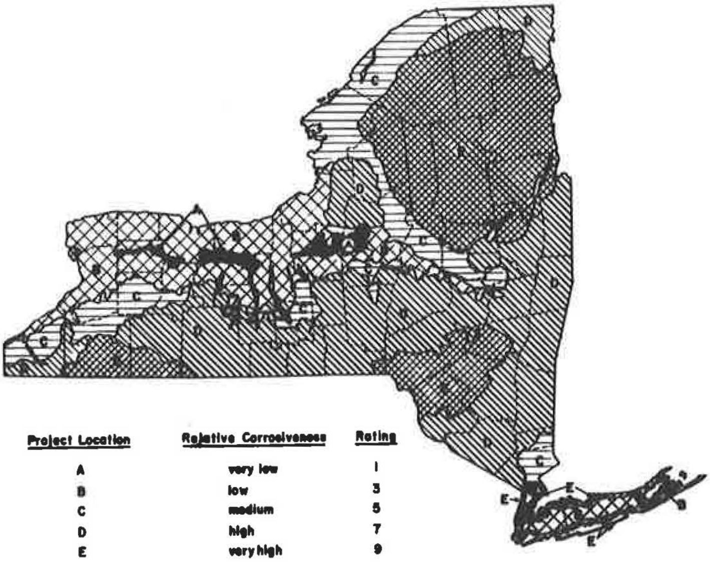
A rating system (durability index) was devised to determine the need to treat steel culverts. The system is intended to supplement experience where it exists and provide a rational substitute where none is available. The durability index represents the sum of the individual numerical ratings assigned to each of the following categories.

1. Surface water corrosiveness rating: The location of the project site on a reference map determines the relative corrosiveness rating, i.e., 1, 3, 5, 7, and 9. The numerical ratings, which are assigned to geographic areas of the state (Fig. 3), are in general accord with available field data and the relative influence of contributing corrosive factors in these areas such as soil types, water hardness, and pH. The designer is cautioned at this stage, however, that abnormally high corrosion rates related to unique local surface water conditions, such as heavy agricultural and industrial water or mine tailings, may necessitate the use of a different pipe material.

2. Abrasiveness rating: This rating category, which receives about half the emphasis of the corrosion category, describes potentially abrasive and nonabrasive bed loads and relates them to the gradient for the numerical rating. An abrasive or nonabrasive bed load with a gradient 2 percent or less has a rating of 1. An abrasive bed load with a gradient between 2 and 4 percent has a rating of 2, whereas the same bed load with a steeper gradient has a rating of 5.

3. Flow rating: This category attempts to recognize the effect of frequency of flow for various applications of pipe usage and is based largely on judgment. Ratings for three conditions of flow and usage are as follows: (a) "highly intermittent" with a rating of 1 applies generally to storm and side drains that are not subject to long-standing water; (b) "intermittent" has a rating of 2 and generally applies to cross culverts carrying streams or small flows that seasonally go dry; and (c) "continuous" with a 3 rating usually applies to cross culverts with stream flows or any long-standing water condition.

Figure 3. Guide map for corrosiveness rating.



4. Service rating: The relative importance of installations is given some recognition in this rating section, again based on judgment. Side drains and driveway pipes are assigned a rating of 1. Cross culverts have a 2 rating.

The durability index is obtained by simply adding the preceding ratings that apply to the site. A durability index of less than 14 indicates that plain galvanized material can be used, whereas a higher rating indicates the need for coatings and invert paving. Extensive experience in a project area, as stated earlier, would possibly modify the decision indicated by the durability index.

The durability design aspects for aluminum material are different from those for steel. The New York height-of-fill-gauge table covers 2⅔- by ½-in. and 9- by 2½-in. corrugation material and has no built-in allowance for metal loss. Currently, asphalt coating and paved invert treatment are only to be considered for the extremes of pH commonly mentioned (6) or where a high abrasion potential exists. This interim approach, which is based on much more limited data, does not necessarily imply that we are not concerned with the durability of aluminum. This is especially true because a recent finding at a few sites in New York has revealed soil-side corrosion at the crown. This phenomenon is thus far unexplained.

A problem that frequently confronts designers in considering the use of steel pipe is the type of corrugation configuration to specify. There is an appreciable overlap of sizes in the different corrugations, and the desirability of one over the other is usually not apparent. This problem is overcome by using the gauge table arrangement shown in Figure 2 and by allowing the contractor to supply any of the structural equivalents for a given size where alternates exist. Economies could be expected with this procedure. Supplying alternates by this method would not be so simple, however, where hydraulic analysis for a given installation reveals the need for different pipe sizes for each corrugation.

Installation requirements and procedures for flexible pipe are also presented on a standard drawing that is automatically made part of the plans. This drawing shows only ordinary bedding including treatment of an unstable soil foundation and rock undercut as well as a trench (sheeted or open cut) and two embankment methods of installation similar to those for rigid pipe. Backfill and compaction criteria are also similar to rigid pipe standards.

Nonroutine Designs

Large pipe culverts of commonly used cross sections under very shallow fills, although designed routinely from allowable fill-height tables, should not be treated as routine installations. Their satisfactory performance under heights of cover between 2 and about 6 ft is credited in large measure to the installation procedures used rather than the design methods, which are even less applicable to this condition. Every known failure experienced on New York highway projects has been attributable to heavy construction loads on pipes with inadequate cover and other substandard installation practices. For this reason, structures in this design situation should be installed in a very closely controlled manner with special provisions made to protect the pipe from construction loads. Warning the contractor is not necessarily sufficient, and consideration should therefore be given to providing temporary ramping details, detours, or other possible protective measures on the plans.

Special shapes, heavier live loads, or large sizes not covered on the fill-height tables of course require individual attention. The most representative of the alternate design procedures available for this situation should be used either for the design or as a check of the design by the more routine methods. Another publication (2) discusses alternate design methods and provides a basis with references for approaching this problem.

Pipes of all sizes and cross sections under very high fills not provided for on standard design tables are occasionally required. Rigid pipes of standard wall-strength design for this case are seldom used because of questions concerning their ability to resist high induced wall stresses and their compatibility with other devices such as the imperfect trench and concrete cradle under very high fills. Davis, Bacher, and Obermuller (7), for example, noted serious rupture of a concrete pipe on a 60-deg cradle at a stage where adjacent sections installed under the same fill height, but without a cradle, were not nearly so distressed. In addition, concern over possible detrimental long-term redistribution of loading effects with the imperfect trench method suggests limitations on its use. Consequently, these cases require a thoroughly analyzed approach, including a possible special design of the pipe itself as well as special installation details. The requirements of a special design for rigid pipe, however, are often too complex and unfamiliar to the average designer, and an alternate such as a box culvert (which is usually overdesigned) or a flexible pipe installation is often selected.

A number of large flexible pipes under very high fills (up to about 140 ft) have been used without incident in New York State. These have been generally designed or reviewed on a project-by-project basis by a central unit that follows the same procedures for structural design as were discussed previously with added emphasis given to soil mechanics considerations.

Special designs should employ engineering judgment in evaluating the anticipated performance of the structure. For example, the construction of a 22-ft span semicircular structural plate arch with abutments founded on rock beneath about 60 ft of fill was recently analyzed. The design analysis provided marginally satisfactory results, but there was concern as to whether a semicircular structure restrained at the abutments could deflect laterally and mobilize adequate passive soil resistance. This was resolved by using either of two alternates, a horseshoe-shaped arch or a round pipe on a prepared bed.

Adverse foundation conditions that present stability and settlement problems for a proposed culvert must of course be resolved prior to installation if problems affecting cost and performance as well as failures are to be avoided. The evaluation and resolution of these problems are based on an analysis of subsurface conditions, which should be part of any important structure design. Such problems are varied and range from removal and backfill of unstable soils to settlement analysis predictions for otherwise stable foundations. Settlement analysis provides the basis for camber recommendations and reveals the possible need for special joints for rigid types where definite tendencies exist for the fill to spread. Standard-type joints used with rigid pipes on steep gradients beneath high fills are also subject to opening, and this possibility should be reviewed. All of the foundation problems that may be encountered cannot be summarized here but can be identified if reviewed by a soils engineer.

Existing pipe culverts are frequently crossed by new highway embankments, which presents a most perplexing problem to the designer. Most of these situations occur with existing reinforced concrete sewer lines, and frequently insufficient data are obtainable on the pipe strength class, bedding type, installation method, and backfill materials, especially if the installation is not recent. This type of analysis, therefore, most often involves many assumptions—beginning with a determination of how much cover could be supported with the known or conservatively assumed pipe strength with a positive projecting (or wide trench) condition and comparing this to the new height of cover. The analysis can go anywhere from this point, but some of the directions it should take are as follows.

1. A determination of the condition of the existing pipe is necessary to see if it is worth saving or to provide a basis for adjusting the assumed or known strength of the pipe. An internal inspection by trained personnel or a television survey may be sufficient if the pipe cannot be occupied.

2. If the approximate analysis indicates that the pipe probably cannot support the new load, some of the possible alternatives, short of replacing the line, include the use of lightweight fill such as expanded shale that has a density of about 70 pcf or cinders at 80 pcf, the imperfect trench used successfully by Spangler for this condition (8), a combination of one or more of the preceding plus lowering the gradeline if feasible, and a protective structural relieving platform (which is usually not economical).

If these or other methods do not provide the desired degree of confidence for an existing pipe in good condition and if the cost of replacement is significant, it may be worthwhile to use load-reducing methods and proceed as planned but monitor the immediate and extended performance of the pipe and assume responsibility for repairs or replacement as necessary. A failure means different things to different people; but in the case of a structurally sound concrete pipe handled in this way, the worst that could be expected to occur where the computed overstress is not unreasonable would be some vertical deformation, crack patterns, and spalling of concrete with possibly some steel exposed. Therefore, repairs would be only a fraction of the total replacement cost. Caution should be exercised before adopting this approach because other factors such as settlement and a reduced diameter, if repairs become necessary, affect the hydraulic capacity. In addition, a period of responsibility must be assumed. This approach, however, has been used successfully on at least one New York State project with large savings and possibly on others.

RESEARCH OBJECTIVES

Current Methods

An attempt has been made here to illustrate the utilization and workability of accepted design methods, particularly when coordinated with construction practice. Deficiencies associated with these design methods were also discussed, and improvements in this area would be of value to the practicing designer. The most notable of these are believed to be the following.

1. A substitute for the 3-edge bearing test that relates more to field conditions would be very desirable and is long overdue.

2. A review and evaluation of current and possibly new bedding methods should be undertaken for rigid pipe. This should include an appraisal of any limitations of concrete cradle bedding as well as consideration of possible benefits from the use of yielding types. The results of a study on this topic should include use criteria that, if of value, can be economically and routinely incorporated into design.

3. A similar review and evaluation of the imperfect trench method is believed to be important because it is so widely used. Its apparent success has been established, but a more uniform methodology is needed to define the best materials to be used, their locations and limits with respect to the pipe, and their possible limitations. Even though this method is usually successful, a few installations in New York exhibited cracking patterns that, although not considered serious, were generally objectionable.

4. Backpacking studies have shown this to be a promising device for both reducing stress and making its distribution more uniform around a structure. A methodology is required for design, materials, and construction practices; it should be incorporated into current design methods, or a new one should be used.

5. It appears that available research results provide an adequate basis for correlating deflection design and field performance, either by recognizing that the E′ values existing in the field are much higher than those suggested for use in design manuals (4, 5) or by using other design methods available. An opinion is offered, therefore, that too much attention and concern are frequently given to the subject of deflection for properly installed flexible pipes.

6. A need exists to improve load analysis procedures for large pipes under very shallow fills where live loads are the principal forces to be resisted. As stated previously, current design methods do not adequately account for this situation, and now that structures are becoming ever larger, these design deficiencies are even more critical.

7. The design of large flexible structures under very high fills (i.e., greater than about 100 ft) is generally accomplished without problems although refinements that would give the vertical load more accurately are desirable.

Rigid pipes under very high fills are not so easily designed because the nonuniform peripheral pressures developed cause large induced wall bending moments that must be resisted. Although backpacking and possibly different bedding methods might assist in overcoming this problem, it would appear desirable to develop a "flexible" reinforced concrete pipe. Prestressed concrete pipe might also offer a greater range of large sizes as well as design advantages under very high fills, and its wider use is suggested where economical.

New Methods

The need for new or improved methods of design has not been generated by a rash of failures. The failures that have occurred are generally attributable to poor installation practices. Advances are desired and necessary, therefore, to obtain better methods that include soil-structure interaction concepts. This objective is well stated elsewhere (2): "The ultimate objective of any culvert design procedure is to predict stresses and deformations at any part of the system at any point in time for a given fill height. . . ." The remainder of this statement details the desired aspects of the theory in a very thorough manner. An added recommendation, however, is that this new method, to whatever extent achieved, be adaptable or reducible to relatively simple terms, graphs, tables, or computer solutions so that standard designs can be established for routine installation situations. The widespread acceptance and adoption of any such new method would thereby be ensured.

New design methods must also place greater emphasis on durability. New York State is continuing its durability studies toward the objective that the design methods described here will become more quantitative, based on the development of a reliable field test program.

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