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PREPARED FOR THE

ENGINEERING DEPARTMENT

OF THE

CITY OF PHOENIX, ARIZONA

BY

ROBERT G. WILLIAMS

CONSULTING ENGINEER

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This is a preliminary draft of an evaluation of pipe for storm drains prepared under contract with the Engineering Department, City of Phoenix, by Robert G. Williams, Consulting Engineer. It does not necessarily represent the views or position of the Engineering Department.

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INTRODUCTION

This preliminary (draft) report consists of a literature review, and subsequent evaluation, of pipes for storm drains for the City of Phoenix. Three types of pipe are considered herein, namely 1) reinforced concrete pipe; 2) cast-in-place concrete pipe (non-reinforced); and 3) corrugated steel pipe.

The literature review included reports, handbooks, and technical bulletins and specifications. It consisted of eight reports from five federal agencies, 19 reports from 11 states, one report from one county storm drainage district, three reports from two cities and nine handbooks, bulletins, and technical specifications from four pipe manufacturers, manufacturers representatives, or national institutes or associations.

The literature review and evaluation, plus the conclusions and recommendations contained in this preliminary report constitutes Phase I of a two-phase project. Phase II will cover a detailed inventory of the existing Phoenix storm drain system (36-inch diameter and larger) followed by a systematic field investigation of selected locations to ascertain the present condition of the pipe. The Phase II portion will include a final report.

In this preliminary report the cited literature is evaluated on the basis of four basic parameters as applied to the three types of pipe. The parameters are; 1) structural adequacy; 2) hydraulic capacity; 3) durability; and 4) economics.

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SECTION I - LITERATURE REVIEW

A. STATE AGENCIES

1. Arizona

a. General

Dana and Peters'[1], in a 1975 study of highway structures including corrugated metal pipe, concluded as follows:

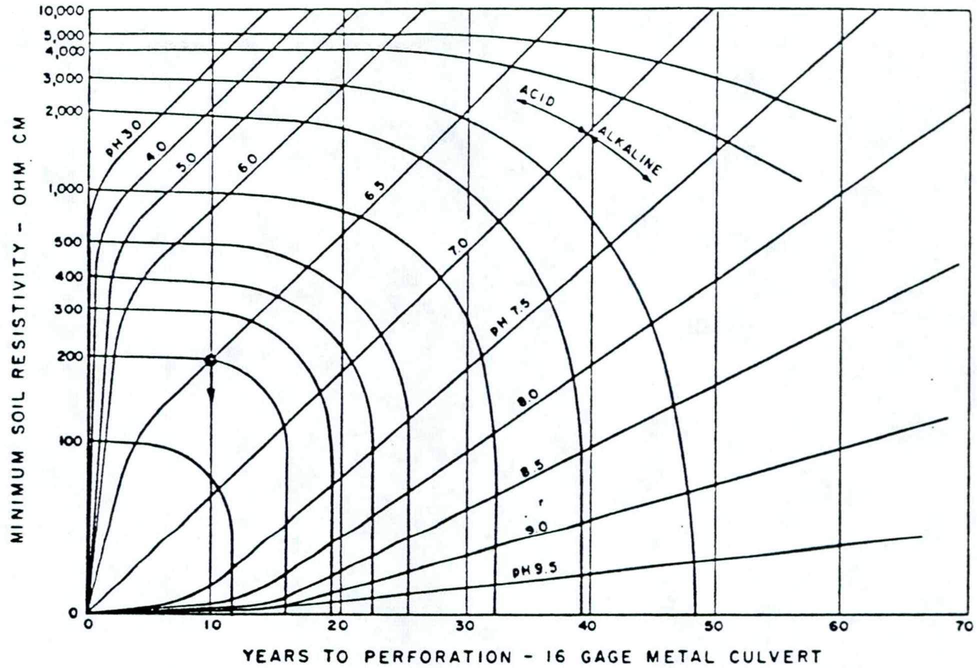
> "The corrosion voltage tests made on galvanized pipe show that most buried pipes have high reaction rates for the first few years in any soil. In medium-and high-resistivity soils (resistivity greater than 2100 ohm-cm) the rate of reaction decreased rapidly after the first few years. In low-density soils (resistivity below 2100 ohm-cm), the corrosion rate usually continues at a high rate even after several years.
>
> The use of bituminous-coated corrugated metal pipe is effective for preventing corrosion in saline soils. In most cases where bituminous-coated galvanized pipes were tested in Arizona, the coating was very effective for prevention of corrosion. No measurable corrosion was found on bituminous-coated galvanized pipes in Arizona. In most cases, the bituminous coating extended the predicted service life of corrugated metal pipe by at least 15 years."

2. California

a. General

Beaton and Stratfull[2] issued a report in 1962 covering a study by the Materials and Research Department of the California Division of Highways which investigated more than 12,000 corrugated metal pipe culverts throughout the state highway system during the previous 35 years. Although they stressed the point that the best criterion for estimating service life of a proposed installation of corrugated metal pipe is an evaluation of existing pipes in the same location, as a result of their evaluation they developed a chart (Plate 1) estimating years to perforation based upon minimum soil resistivity and pH. This chart has been used with varying degrees of success by other state highway departments. The authors also concluded that bituminous coatings on the average to add six years to the life of CMP culverts, with a range of from nearly zero to over 20 years.

Subsequent to the 1962 report by Beaton and Stratfull, the California Department of Transportation (Caltran) issued a manual, "Highway Design Manual" in which there appears a chart titled "CHART FOR ESTIMATING YEARS TO PERFORATION OF CORRUGATED STEEL PIPE".[39] The chart carries a date of April 2, 1979, and is identified in the manual as Figure 7-351.3 (See Plate 2).



EXAMPLE: Given, pH = 6.5 & Resistivity = 200 ohm cm
Then 16 gage CMP perforated in 10 years.
For a culvert metal gage of 12 multiply
years by factor below. i.e. 1.8 x 10 = 18 years

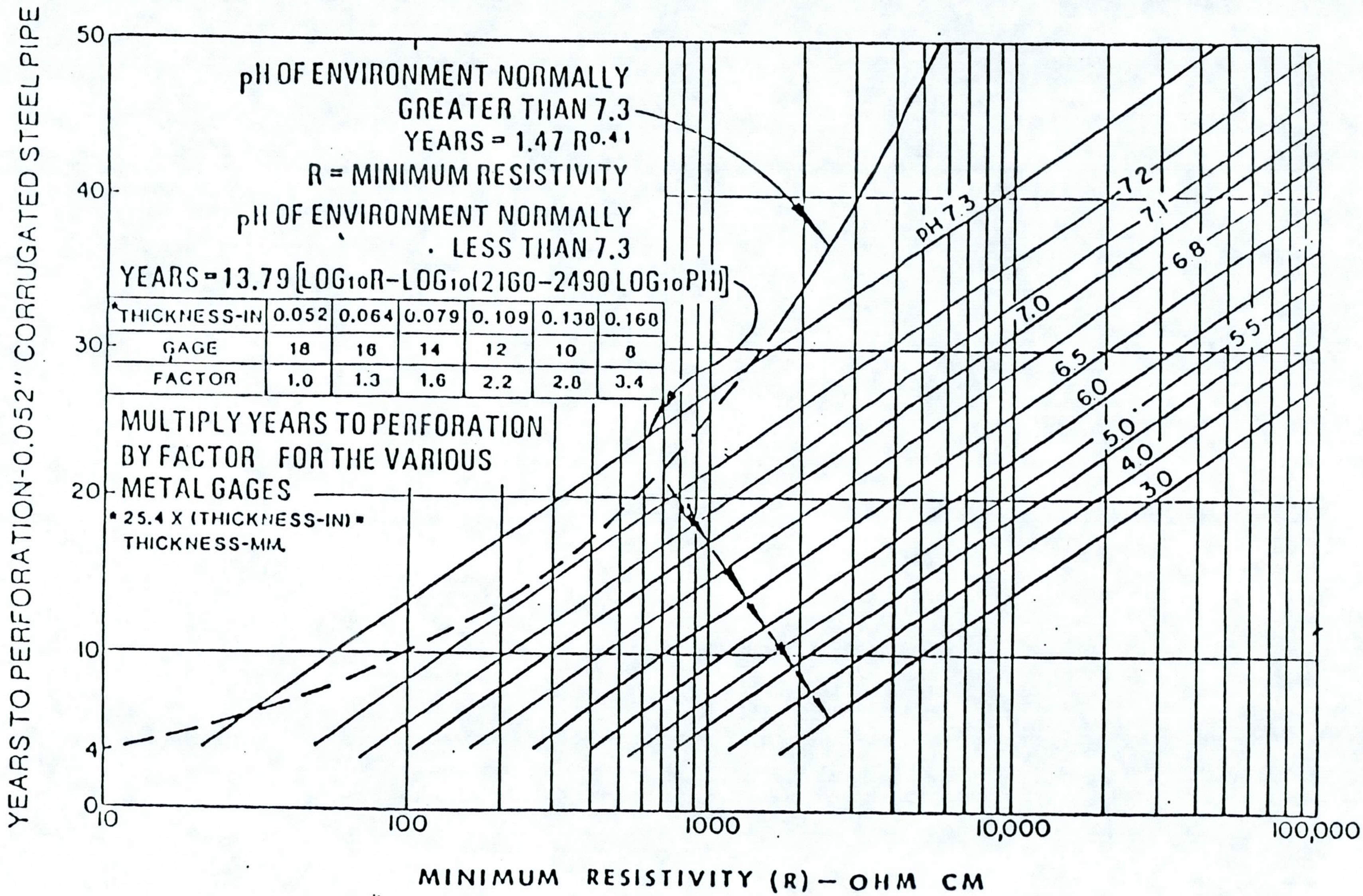
Gage	14	12	10	8	6	2	0	000
Factor	1.3	1.8	2.3	2.8	3.3	4.3	5.0	6.0

Figure 6. Chart for estimating metal culvert corrosion rate.

collapse or that its usefulness as a carrier of water will cease. Instead, this terminology of years-to-perforation is used as a common yardstick for all culverts. If the arching action of a fill is sufficiently substantial to warrant disregard of a perforation or loss of the culvert invert, then the arching action of the fill could be considered in the mechanics of the design.

For the present, it is concluded that there is a linear relationship between service life and the thickness of metal. For example, it is assumed that in the same environment a metal culvert of 8-gage thickness will last about three times longer than a culvert of 16-gage thickness. It is believed that there are locations in which the time to perforation of the culvert metal will not be proportional to the metal thickness. It is not known, however, whether the deviation between the corrosion rate and the metal thickness will consistenly favor an added or reduced perforation time. For instance, Romanoff (*2*, Figs. 11, 52, and 56) shows that the underground corrosion rate of steel and galvanized steel generally is relatively linear with time after ap-

PLATE 2



*THICKNESS-IN	0.052	0.064	0.079	0.109	0.138	0.160
GAGE	18	16	14	12	10	8
FACTOR	1.0	1.3	1.6	2.2	2.8	3.4

REFERENCE: TEST METHOD NO. CALIF. 643

CHART FOR ESTIMATING YEARS TO PERFORATION OF CORRUGATED STEEL PIPE

April 2, 1979

3. Colorado

a. General

In 1968 the Colorado State Department of Highways issued a Research Report[3] titled "CULVERT PERFORMANCE AT TEST SITES IN COLORADO". The report covered culvert performance from 1962 to 1968, a period of six years. According to the report some areas of Colorado have soils of very high alkalinity, and in which areas uncoated galvanized steel culverts have corroded rapidly. Uncoated galvanized steel culverts do perform satisfactorily (to date) in the remaining areas of the state.

b. Conclusions

The conclusions contained in the report are as follows:

"i. Asbestos-bonded asphalt-dipped corrugated-steel and reinforced concrete culverts are particularly durable for use in roadway construction.

ii. Except where alkalinity is unusually high, corrugated steel and aluminum culverts perform well. Aluminum culverts do not appear to have the resiliency of steel culverts and require a minimum of two feet of cover to avoid damage. It has an advantage in ease of installation in that generally only manual labor is required to handle and place aluminum culverts of short length and small diameter. Additional care in backfilling is necessary to prevent denting and deforming aluminum culverts, however.

iii. The stainless steel culverts observed at test sites in

Colorado since 1965 have shown considerable corrosion when placed in an alkaline environment. Their performance will continue to be observed and reported."

4. Idaho

a. General

The State of Idaho Department of Highways issued a report[4] dated April 1965 based upon their study of the durability of metal pipe culverts.

b. Conclusions

Their conclusions were as follows:

"i. The performance of galvanized metal pipe in service indicates a life as follows:

- Desert Land - 40 to 60+ years.
- Cultivated Land - 20 to 60+ years.
- Timbered - 25 to 60+ years.
- Pasture - 30 to 50 years.

ii. Actual age of pipe (except for five installations) is less than predicted by 10-25 years and they are reported to be in fair to excellent condition.

iii. The only installation indicating a service life less than 40 years are timbered areas, pasture lands, and some cultivated soils.

iv. It appears that the service life of corrugated metal pipe with galvanized coating is giving good to excellent service with many installations having served in excess of 30 years and no evidence of serious distress during this investigation."

c. Recommendations

Their recommendations were:

"It is recommended that the California test and criteria be used as a guide to the service life of pipe."

"Asphalt coating is recommended to extend the service life wherein the service life predicted is less than 40 years."

5. Kansas

a. Report No. 1

i. Abstract

Herbert E. Worley, Soils Research Engineer for the Kansas State Highway Commission, prepared a report[5] dated 1970 on the effectiveness of bituminous coatings on corrugated metal pipe. The abstract of the report reads as follows:

"More than 500 asphaltic bituminous coated pipes were inspected on highway projects in Kansas. Inside coatings were good on only twelve percent of those pipes three and four years old, and on none of the older ones. Inasmuch as the coatings are usually intact for less than three years, they are of little value, and we recommend that their use be discontinued."

b. Report No. 2

i. General

Herbert E. Worley, Soils Research Engineer for the Kansas

State Highway Commission prepared another report[6] dated 1971 titled "Corrosion of Corrugated Metal Pipe." The report concluded as follows:

- "Little significance was seen in variations of either pH or resistivity in their effect on corrugated metal pipe life in Kansas. All but two measured values of pH were between 5.7 and 8.5 and 90 percent of resistivities were between 700 and 2300. Within these ranges corrosion was not sufficient to determine a correlation such as indicated by the California chart. No corrosion was found on any of the aluminum pipes, all of which were seven years or less in age. In three surveys of galvanized steel pipe covering 43 years of service, in 35 counties well distributed over the state, 929 pipes were inspected but only 19 perforated ones were found. Most of them were in the vicinity of coal mines. All of them were serviceable. None had failed structurally."

  "This record of service indicates that corrugated metal pipe with normal galvanizing is satisfactory for most of Kansas except in the immediate vicinity of coal mines." ...... "A life of 40 to 50 years or more may be anticipated for normal galvanized steel pipe in Kansas at most locations other than near active coal mines."

6. Louisiana

Richard W. Kinchen, Pavement Research Engineer with the Louisiana Department of Transportation and Development presented a paper[7] at the 59th Annual Meeting of the Transportation Research Board, January, 1980. The study involved ten types of aluminum and galvanized steel culverts with various coatings. The test results were generally satisfactory, however the test period was only six years and therefore of limited value.

7. Maryland

The Maryland State Road Commission, Bureau of Research, issued a report[8] in April, 1971 - "Statewide Survey of Bituminous-Coated only, and Bituminous-Coated and Paved Corrugated Pipe." Their conclusions were as follows:

"i. Results showed that bituminous-coated and paved pipes are superior to bituminous-coated only pipes insofar as retention of coatings is concerned.

ii. Indications are that the coatings add only four years or less to the life of the majority of pipes which are bituminous coated only.

iii. Indications are that the increase in life of the majority of bituminous-coated and paved pipes is eight years or less.

iv. Age appears to have a significant influence on the coating condition of both classes of pipes. Both the number of pipes with loss, and the amount of loss increase appreciably with age.

v. The coatings on the structural plate pipes did not perform as satisfactorily as the coatings on the other pipes.

vi. The results showed that abrasion is not the only contributor to coating loss. Considerable loss is also due to lack of adhesion between the coating and the metal.

vii. It appears that the increased cost of bituminous coatings is not warranted."

Their recommendation was ".... that asphalt coatings on corrugated metal pipes be discontinued for highway construction in Maryland."

8. Michigan

In 1974 an Interim Report[9] was prepared by Noyce and Ostrowski for the Michigan Department of State Highways and Transportation. A study was performed on 277 galvanized metal culverts ranging in age from 10 to 14 years. Unfortunately, the report is stamped "NOT FOR PUBLICATION". Therefore their findings are not reported here.

9. New York

a. Summary

Two Reports[10,11] were published by the New York State Department of Transportation in 1984, in cooperation with the Federal Highway Administration. The first report concluded that bituminous-coating and paving adds 30 years of life to round pipe on the state system, and adds 20 years of life to pipe arches. Beyond 30 years, paving is ineffective in protecting corrugated steel pipe. The second report determined that on a probabilistic basis the state could be divided into two zones, with Zone I being assigned a metal loss rate (steel pipe) of 2 mils/year, and for Zone II a metal loss rate of 4 mils/year. The report concluded from their field studies that 90 percent of all steel culverts will have losses equal to or less than the selected rates. The study also established an end point to the service life of steel culverts for design purposes. The end point is defined as the point when the culvert invert or flow line would be completely removed if the design metal loss (2 or 4 mils/year) occurred uniformly throughout the length of the culvert.

A metal loss rate for aluminum pipe culverts was selected to be 0.5 mil/year, with the end point determined in a similar manner to steel pipe culverts.

10. Ohio

Five Reports[12,13,14,15,16] were published by the State of Ohio Department of Transportation between 1972 and 1986.

a. Report No. 1

The first report, by Meacham et al dated December 1972 was an interim report containing descriptive information regarding establishing procedures for performing the planned statewide field study.

i. Observations

However a "Preliminary Report Critique" was included which contained observations and recommendations made during the course of the field study. Some of these were as follows:

- "Coating of corrugated steel pipe without paving should be discontinued in most cases. Our investigation, plus conversations with various field division personnel, has revealed that coating on the interior of a pipe has very little permanence and its effectiveness is lost in a relative short time. If corrosive elements are expected or known to be present around the exterior of the pipe, then coating should be considered for the protection it would provide the pipe against attack from without."
- "We recommend manufacturing controls on the method of coating and paving of corrugated steel pipe be added to the Ohio specifications. We believe that part of the adherence problems of coating and paving to the metal is due to poor manufacturing controls at the time the pipe is coated and paved."
- "Most occurrences of severe corrosion that we have observed in corrugated steel pipe has been on pipe which was never protected (beyond galvanizing) or on pipe which had lost its coating and/or paving. Most occurrences of coating and paving losses were attributed to abrasion, erosion and/or poor adherence problems. Where the coating and/or paving properly adhered to the pipe, the pipe usually was in good to

excellent condition. For severe corrosive or abrasive environments we recommend bituminous coated asbestos bonded pipe be used."

b. Report No. 2

The second report, dated January 1982, by D.G. Meacham et al, covered in excellent detail the preparation steps leading up to the field survey.

i. Preparation Steps for Field Survey

Chapter 2, Investigation Procedures and Observations covered the Preparation Phase, (Inventory Data Accumulation, Selection of Culverts to be Field Inspected. Determination of Field Data Desired, Determination of Inspection Procedures, and Selection of Personnel and Equipment), Field Inspection Phase (Plotting of Site Locations, Scheduling of Field Trips, Obtaining Field Data, Laboratory Analysis of Field Data, and Maintaining Equipment), Observations (Visual Rating System, Factors Affecting Pipe Life, Bituminous Coatings, and Sedimentation).

ii. "Conclusions

Based on analyses of data and observations made by field crews during the field inspection phase, the following conclusions are presented with regard to the performances of conventional bituminous protection of corrugated metal (steel) pipe, galvanized corrugated metal (steel) pipe, reinforced concrete pipe and other types of culvert protection and a brief discussion on environmental factors affecting culvert performance.

- Conventional Bituminous Protection for Corrugated Steel Pipe.

  The age of bituminous coating was the only variable with a statistically significant effect on the condition (protection rating) of this type of protection. Since the correlation between age and protection rating was so low (see "Results of Analysis for Bituminous Protection of Pipes"), however, the only meaningful relationship which could be developed to predict useful life of bituminous coating was that of "% not poor" versus age (equation 2 of text). From this relationship the average useful life (expected years to poor condition) was 3.16 years with a 50% chance of the coating remaining useful for 1.5 years or more and only a 20% chance of it remaining useful five or more years. Therefore, bituminous coating, without invert paving, appears to be of little value.

  For bituminous coatings with paved inverts three variables exhibited statistically significant effects on the condition of the protection. These were, in order of importance, age (very large negative effect), sum of sediment depth and flow depth (large negative effect), and abrasion (minor negative effect). The significant effect of the sum of sediment and flow depth concurs with the observation made by field crews that coating and paving performed much better for those culverts where the normal dry weather flow had been contained within the paved portion of the pipe. The near negligible effect of abrasion on the condition of coating with paving and the lack of any significant effect of abrasion on the coating substantiated the observation made by the field crews that the major problem with conventional bituminous protection is one of adherence and not wear. At the vast majority of sites where bituminous protection was observed and cause for loss could be determined, the protection had not been worn away but had become checked (cracked), lost its adherence to the metal and been washed out in chunks. This does, however, appear to contradict the observation made by field crews that abrasive flows have an accelerating effect on the deterioration of bituminous paving.

Although the correlation between the condition (protection rating) of coating with paving and the independent variables was improved over that for coating only, it was still not high enough to predict the rating of protection for any individual culvert. Therefore, the same relationship (% not poor versus age) used for coating was applied to coating with paving. Three relationships were developed; for all coated and paved culverts (equation 4), for those coated and paved culverts where dry weather flow had remained within the paved portion of the culvert and for those where it had not (see Plate 3). From these relationships the average useful life of bituminous coating and paving was determined to be 19 years for all cases, 25 years where dry weather flow was contained in the paved portion, and 12 years where dry weather flow overtopped the paved portion.

Because of the small number of coated and paved culverts where paving had been eroded, no analysis was possible to determine the effect of abrasion where adherence problems had not occurred first. However, should adherence problems be corrected the expected (average) useful life of coating and paving under normal flow conditions (without excessive sediment or flow backup) should be in excess of 25 years. Therefore, conventional bituminous coating with paving appears to be quite useful as culvert protection.

- Corrugated Steel Culverts

Comparison of visual metal ratings to actual measured metal loss indicated that visual ratings are a suitable, fast and inexpensive way of determining the condition of a metal culvert. However, quite a bit of overlap existed for metal losses of culverts rated good and fair. More consistent results (rating versus

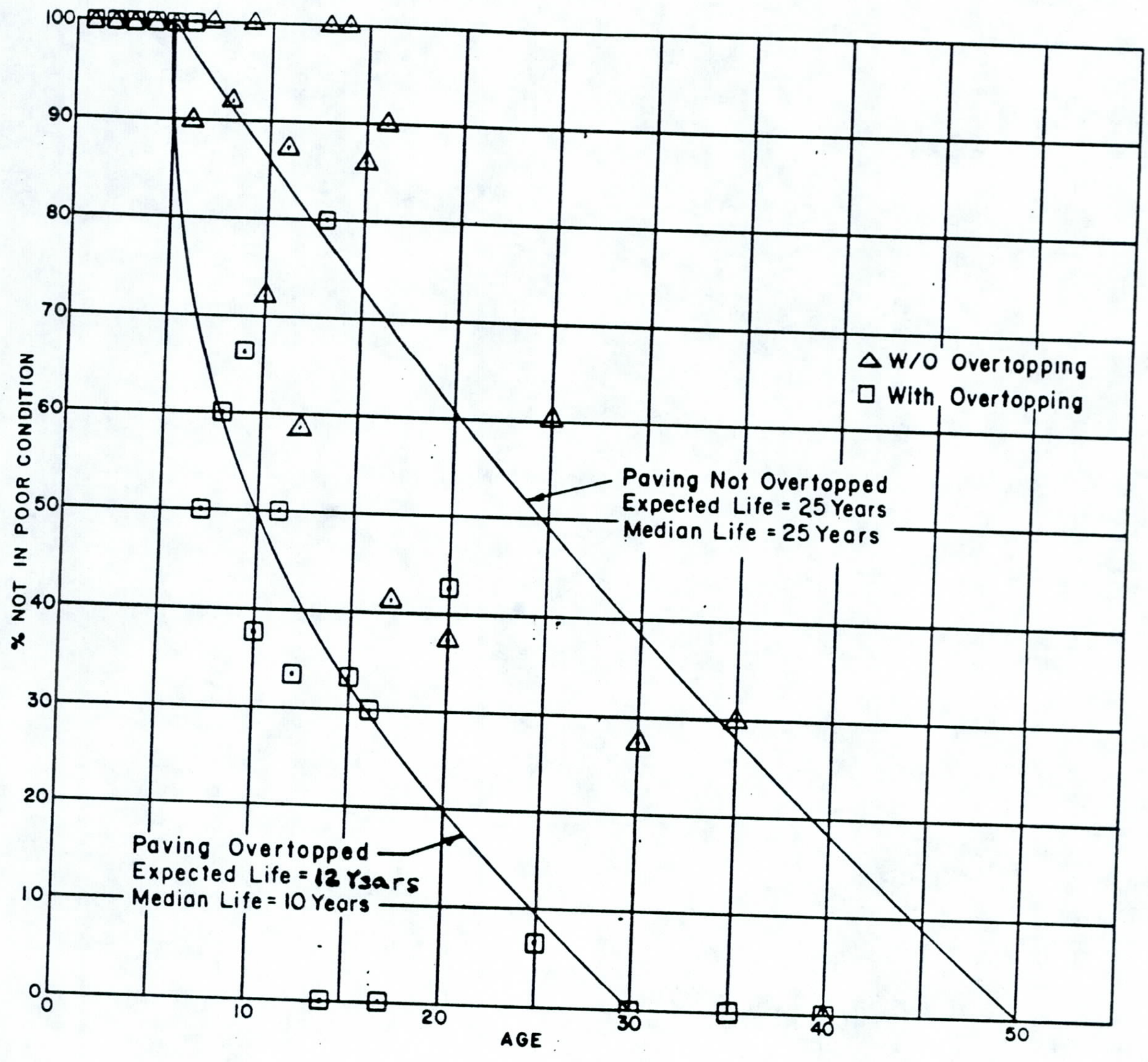


Figure 11. Percentage of bituminous coated and paved culverts with protection not rated Poor (Overtopping considered).

metal loss) might have been obtained had additional categories been assigned to various degrees of rust and scale between no observation of loss and perforation. These results and later comparisons of predictive equations developed from both ratings and metal loss show the absolute necessity of basing any predictive model for steel pipe life on actual metal loss in lieu of a visual rating system.

There was a significant difference in the performance of corrugated metal pipe (2-2/3" x 1/2" corrugations) and structural plate pipe (6" x 2" corrugations). In general, structural plate pipes performed only slightly better than CMP's except in the case of high pH (pH>7.0) non-abrasive flow where the SPP's exhibited much less metal loss and much better ratings than CMP's. This is probably due to the structural plate pipe having superior galvanizing, which is most effective in high pH low abrasive flow.

As expected, the type of pipe protection used (galvanized only, coated, coated and paved) had a strong effect on metal pipe performance. To account for this effect in later analyses, the age of the pipe was adjusted by subtracting the average time the protection could be expected to keep the metal unexposed to the flow. From this point on in this discussion, age will actually mean years that the metal itself was exposed to flow.

Also, as expected, age had the largest effect on culvert condition (rating and measured metal loss). The only two environmental parameters having consistent significant effects on metal condition were water pH and abrasion, which substantiates the observations made by field crews. The effect of water pH was significant throughout its range (2.5 to 9.0) with culvert condition being worse as pH decreased (acid content increased). The presence of abrasive flow had a detrimental effect on metal condition that was most pronounced for higher pH flows.

The effect of pipe slope on metal condition was inconsistent in the analyses performed. Although pipe slope is probably a factor in metal life, further experimentation is necessary to determine exactly what effect it does have. However, the strong effect of abrasion for which pipe slope could be an indicator may have "absorbed" some of the effect which could be attributed to slope.

The predictive models developed for determining metal loss (equations 6, 7, 8 and 9; Plate 4 and 5) were, therefore, based on measured metal loss as a function of age and pH for CMP's with abrasion, CMP's without abrasion, SPP's with abrasion, and SPP's without abrasion. It should be noted that since the field

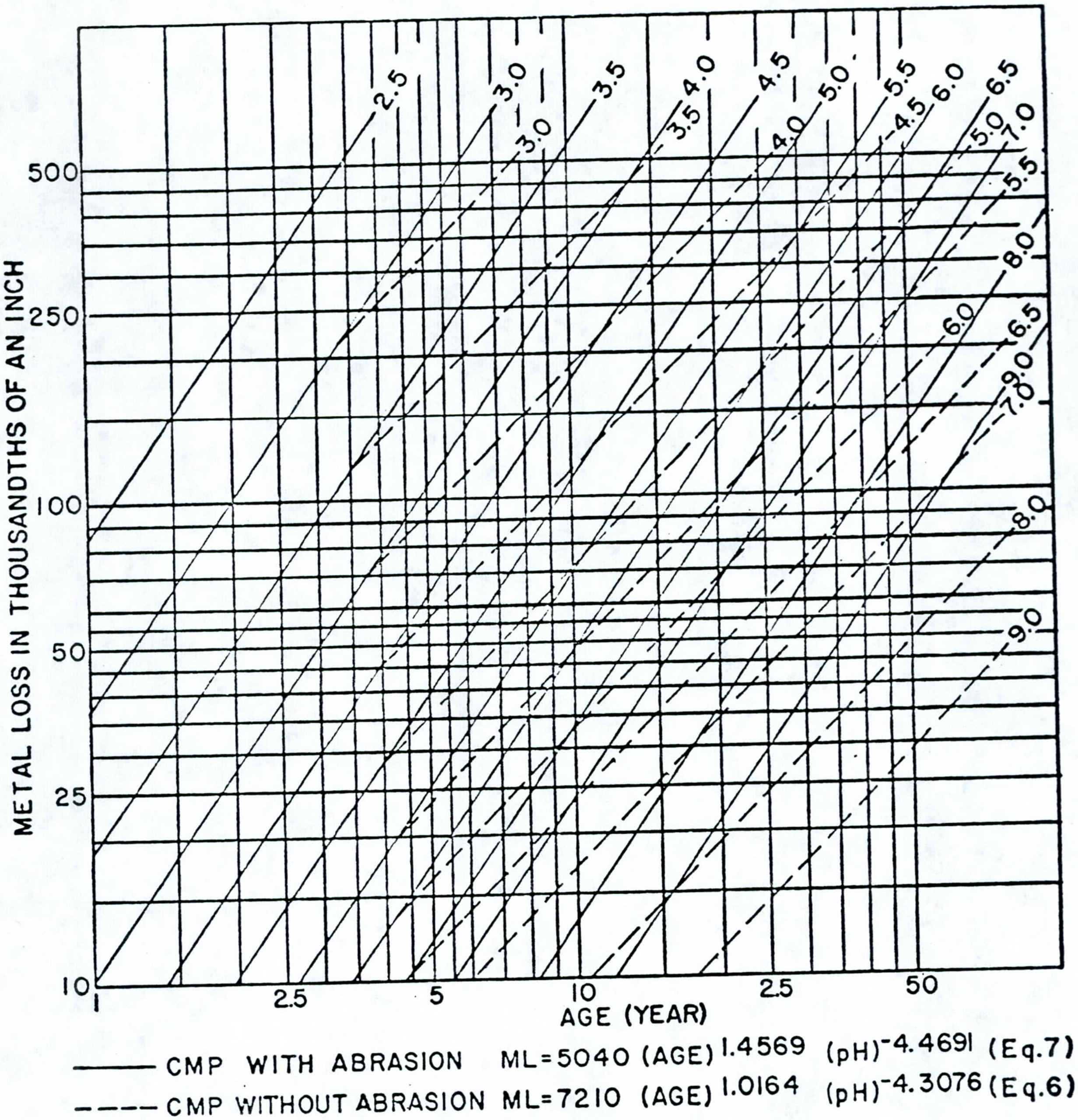


Figure 23. Predicted metal loss for corrugated metal pipe (CMP) culverts.

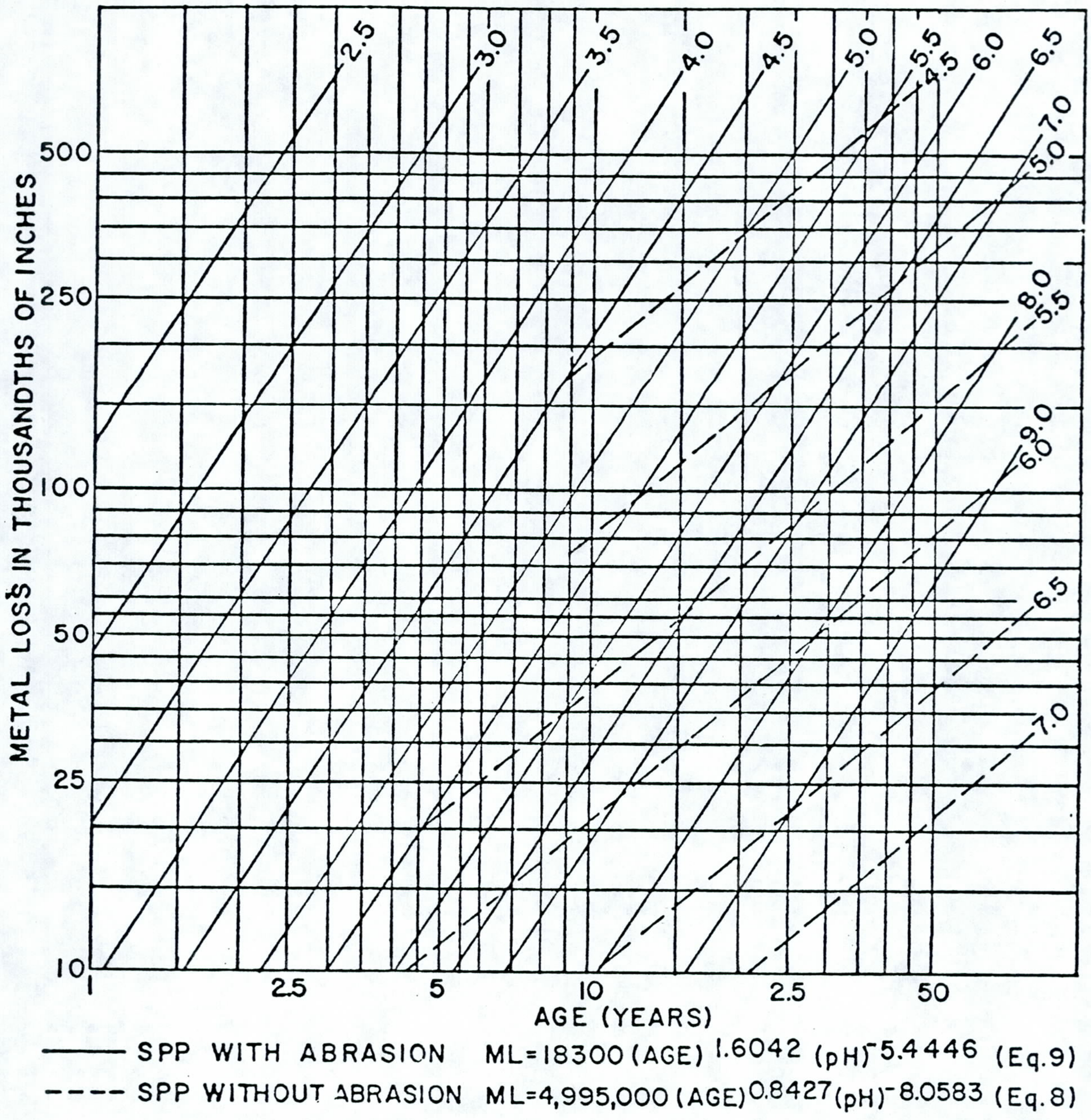


Figure 24. Predicted metal loss for structural plate pipe (SPP) culverts.

data listed only abrasion a factor (yes or no), a subjective decision must be used in applying these models. The models proved to fit the data quite well (Table 4 not reproduced herein).

One additional observation made for metal culverts during the field inspection phase is worth noting. Little, if any, metal loss was observed on the upper one-half of the interior of these pipes and little, if any, loss on the exterior of those pipes cored. It would, therefore, appear that coating the upper one-half of a corrugated steel pipe is unnecessary.

- Reinforced Concrete Pipe

Since it would have been next to impossible to obtain sample cores from in place concrete pipe to determine actual concrete loss, concrete ratings were analyzed to determine the durability of concrete culverts. The behavior of concrete pipes differed for two environmental groups: Water pH greater than 7.0 and water pH less than 7.0.

For pH greater than 7.0 (actually 7.0 to 9.5) age was the only variable having a significant effect on concrete rating. Slope, flow velocity and abrasion, in that order, contributed a significant, but minor, effect on concrete rating. The regression equation relating concrete rating to the other four variables (equation 13) did not produce a high enough correlation to be used in predicting the condition of a culvert.

For water pH less than 7.0 (acidic conditions) water pH had the greatest significant effect on concrete rating. As pH decreased ratings became worse at an increasing rate and reached a stage where protection should be considered between 4.5 and 4.0. Pipe slope contributed the next greatest effect, with sediment depth (positive) and age (negative) the only other variables contributing significant effects. The fact that abrasion was not a factor here and had only minor effect for pH greater than 7.0 is probably due to two factors: the effect of abrasion is difficult to observe in concrete culverts and these culverts being smooth tends to allow bed load to roll along the bottom of the pipe instead of bouncing off corrugations as in metal pipes. The strong effect of pipe slope (which is the nearest indicator of abrasion) for concrete pipe should indicate that abrasion may well be a factor although the analysis does not substantiate it.

Because of the severe effect of the lower pH range on concrete culverts, a predictive model for the life of concrete pipe was necessary. Fortunately, because of the high correlation between observed concrete rating and that predicted by the regression equations relating concrete rating to the four independent variables, this was not a problem. Since any excessive sediment depth is a hydraulically undesirable condition and cannot be predicted, the life of concrete pipe (years to poor) was then plotted versus slope and pH, with sediment depth set equal to zero (see Plate 6 and 7)."

- Other Types of Culvert Protection

  Several additional types of culvert protection, other than bituminous coatings with or without paving, were observed. Although statistical analyses were not possible because of lack of sufficient data, several observations were presented here.

  - Reinforced Concrete Culverts with Vitrified Clay Liner Plates

    These culverts have performed very well. Most were installed in extremely harsh conditions and as yet none have shown any adverse reactions except in one case where the dry weather flow had overtopped the liner plates because of sediment build-up.

  - Concrete Field Paving of Reinforced Concrete Pipe

    The concrete paving, although extending the life of the pipe under extremely acidic conditions, deteriorates at a faster rate than the pipe itself and can only be considered as a stopgap

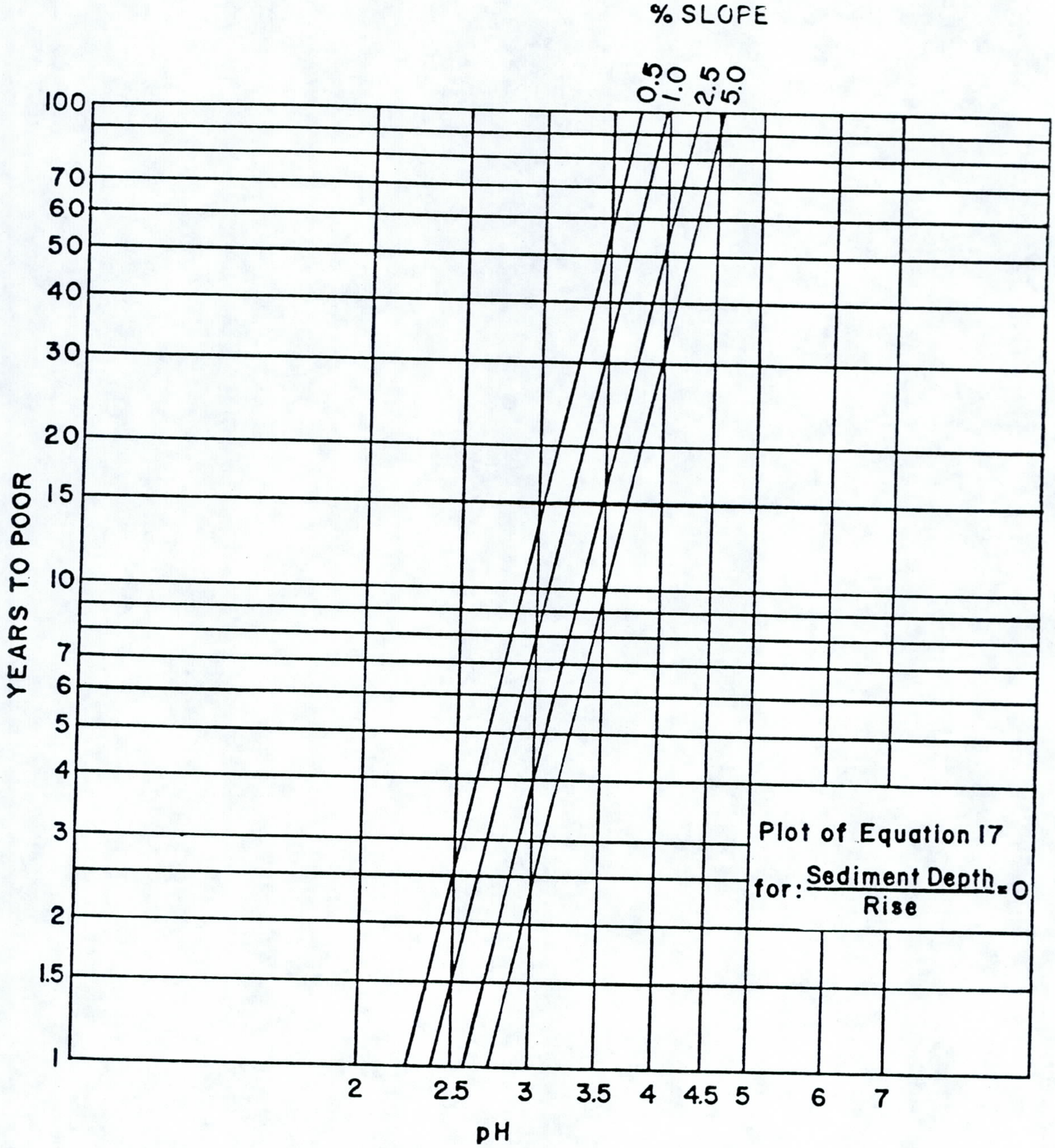


Figure 30. Plot of Predictive Equation 17 for concrete pipe culvert life.

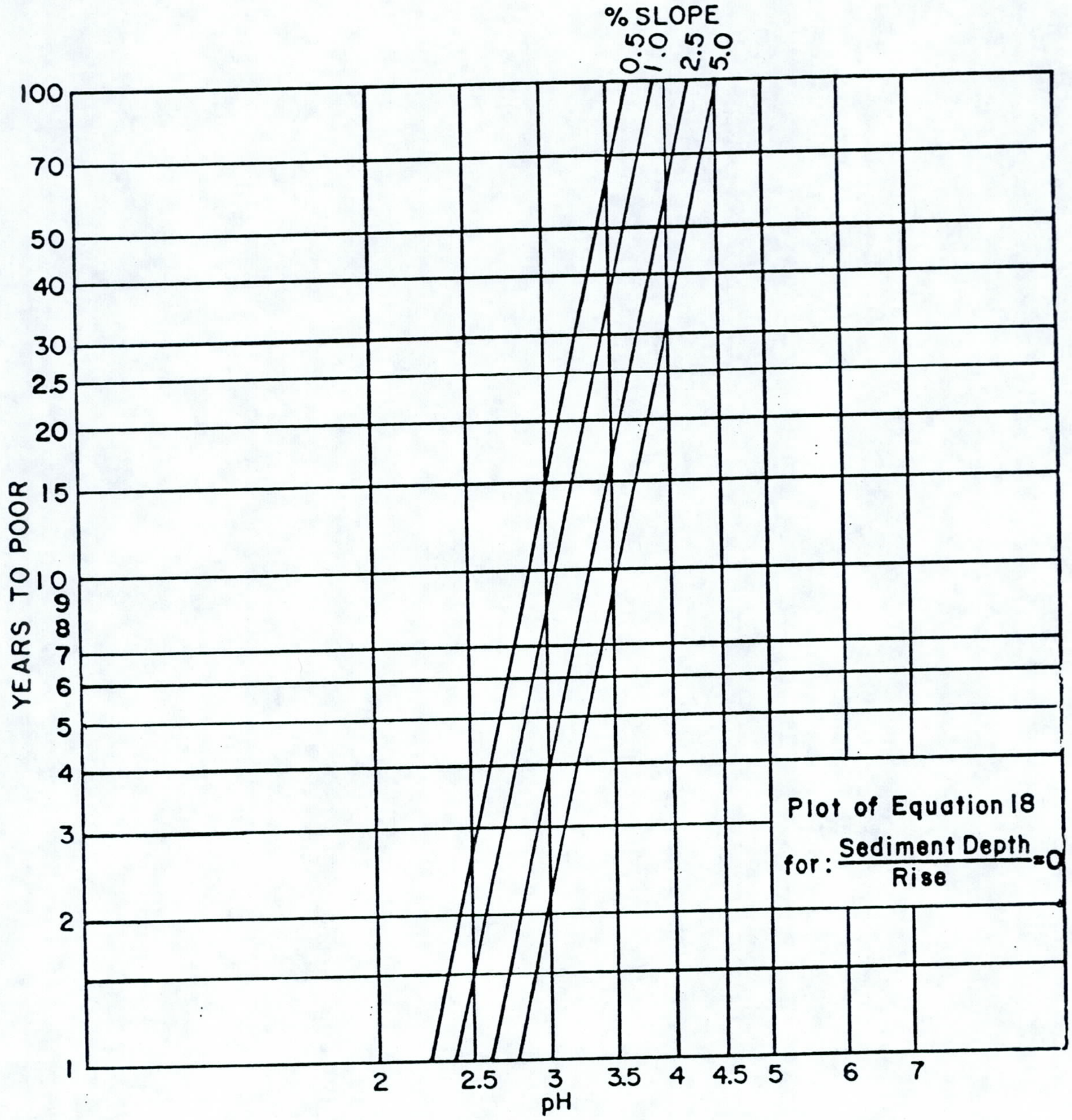


Figure 31. Plot of Predictive Equation 18 for concrete pipe culvert life.

measure.

- Coal Tar Pitch Coating

  This type of coating has been applied to the interior surface of concrete pipe in a few installations in Ohio. The coating has performed poorly (about as badly as bituminous coating for corrugated steel pipe). In no case observed did it last more than five years.

- Bituminous Coating of Structural Plate Pipe

  This type of coating has performed just as poorly on SPP as it has on CMP.

- Bituminous Sand Asphalt Field Paving

  This type of material has been used to pave the invert of several structural plate pipe culverts. It has not performed as well as could be expected, probably due to the fact that proper compaction is difficult to obtain.

- Concrete Field Paving of Structural Plate Pipe

  The concrete paving has performed better than sand asphalt paving. In areas of very low pH, concrete field paving with a vitrified clay lined trough for low flow has performed very well where observed.

- Asbestos Bonded Bituminous Coating and Paving

  This type of protection is factory applied to corrugated steel pipe and has performed very well. The asbestos fibers, which are embedded in the molten zinc during galvanizing, appear to have corrected the problem of adherence of bituminous protection previously noted. The paving showed little wear from the flow, but more data needs to be collected before any accurate estimate can be made of the life of bituminous protection which stays on long enough to be worn away. However, it would appear that the average life of the coating and paving would exceed 25 years, extending the total life of the culvert by this number of years.

. Thermoplastic Coating

This type of protection is applied to the steel sheets from which corrugated steel pipe is formed. In general, the coating has performed well under non-abrasive low pH conditions. However, three types of problems exist for this material. First, the forming of lock seams on helically corrugated pipe appears to have a detrimental effect on the bond between the thermoplastic coating and the metal along the seam. This ranges from unobservable holidays (voids and cracks) to complete loss of the coating on the seam. This problem is compounded after installation by abrasive flow conditions.

Second, the exposed edges of plates in riveted annular corrugated pipe are susceptible to delamination under abrasive conditions. Furthermore, rivets are totally unprotected and conventional rivets deteriorate under low pH flow. Third, the thermoplastic itself has been susceptible to wear in abrasive flow. Extremely rocky flow has rendered the protection on three culverts totally useless within one to five years. Other sites also have shown some wear on the protection where less severe abrasive flow existed. To date, no observed wear has occurred for abrasive flows carrying only stones of 1" to 2" or less in diameter."

iii. "Recommendations

Based on the previous conclusions the following recommendations are made. They are those of the authors and do not necessarily reflect the views or policies of the Ohio Department of Transportation.

- Because of the extremely short useful lives of plain bituminous coating on corrugated steel pipe and structural plate pipe and coal tar pitch on concrete pipe, any use of these types of protection should be discontinued.
- Since nearly all observed deterioration of metal

culvert pipes has occurred on the interior bottom half, protection is necessary on only the bottom half to adequately protect the vast majority of metal culverts in Ohio. An exception to this rule would be where corrosive backfill might be expected. In this case, protection should be applied to the entire pipe, exterior and interior.

While coating only the bottom half of culvert pipes will save only a few cents per foot of pipe, it could add up to an appreciable amount in a year's time considering the total number of feet of culvert used on the highway system.

- Adherence of conventional bituminous coating and paving to corrugated steel pipe is by far the biggest problem affecting the life of this type of protection. However, the span of time the coating and paving remained on the pipe varied considerably indicating adherence problems may well be due to poor manufacturing procedures. Therefore, more consistent quality control measures should be applied with conventional bituminous protection. To achieve higher quality procedures, we recommend manufacturing controls on the method of coating and paving of corrugated steel pipe be added to the Ohio Specifications. We recommend this specification include, as a minimum, the following requirements:

The bituminous material for coating shall meet the requirements of AASHTO M 190. When applied to the pipe the bituminous material shall be free of impurities and the metal shall be free from grease, dirt, dust, moisture or other foreign matter. The pipe shall be cleaned immediately prior to the dipping process. Either process as set out below may be used for application of the bituminous material.

- When the pipe is not preheated, the temperature of the asphalt at the time of immersion shall be 400± degrees F. and the duration of the immersion in the asphalt shall conform to the following:

Metal Thickness (inches)	Gage	Minimum Time in Minutes for Metal to be Immersed in Asphalt for First Dip
0.064	16	2.5
0.079	14	3.0
0.109	12	5.0
0.138	10	6.5
0.168	8	8.0

- When the pipe is preheated, it shall be brought to a temperature of 300 degrees F. and the asphalt shall have a temperature of 380 degrees F.± 5 degrees F. before dipping of the pipe.

  The pipe shall be dipped a second time, if necessary to give a minimum thickness of 0.05 inches.

  When asbestos bonded bituminous coating is specified the above requirements shall equally apply and, in addition, the special process of embedding asbestos fibers in the molten zinc shall be used to bond the bituminous coating.

- Because the effect of dry weather flow overtopping the paving in coated and paved culverts substantially reduced the effective life of the protection, increasing the height of paving on the sides of the culverts would extend the useful life of the protection at many installations. Current specifications call for at least 25% of the circumference of a circular pipe and 40% of the circumference of a pipe arch to be paved in the invert. We recommend that the ODOT Specifications be changed, by modification of AASHTO Specification M 190, to provide for at least 33% of the circumference of a circular pipe and 45% of the circumference of a pipe arch to be paved in the invert. Paving 33% of the circumference of circular pipes will extend the paving 10% higher on each side than now provided by specifications. Paving 45% of the circumference of pipe arches will extend the paving so that it will approximately reach the springline of the pipe arch on each side.

  No study has been made to determine the additional cost of extending the bituminous paving for corrugated steel culverts. However, since bituminous coated and paved CSP should not be specified unless needed to protect the pipe in adverse environmental conditions, it is logical to assume that replacing an unprotected pipe would cost much more than the increase in paving costs.

- Conventional bituminous coating and paving is suitable for corrugated steel pipe where pH is above 5.5 but some type of protection is necessary. For conditions with pH less than 5.5 asbestos bonded bituminous coating and paving is recommended.
- For low pH conditions without abrasion thermoplastic coatings can be used on corrugated steel pipe. However, the lock seam on helically corrugated pipe should be thoroughly checked for delamination and improved manufacturing controls instituted if this continues to be a problem. Also, rivets in annular corrugated pipe should be made from stainless steel, or otherwise suitably protected. The use of thermoplastic coatings is not recommended for sites with abrasive flow (bed loads with stones greater than 1" to 2" in diameter) unless a bituminous paved invert with adherence properties similar to asbestos bonding can be provided.
- Concrete field paving is recommended over sand asphalt for structural plate pipe where pH is between 4.0 and 5.5. For pH less than 4.0 a vitrified clay liner

trough in the concrete paving is recommended.

- Because concrete paving deteriorates faster under extremely caustic conditions than the concrete pipe in which it is installed, vitrified clay liner plates are recommended for concrete pipe installed at sites with pH less than 4.0. Epoxy coating of concrete pipe may be a suitable alternate to vitrified clay liner plates, but to date performance remains questionable due to only recent installation.
- Structural plate pipe performed much better than corrugated steel pipe in areas with higher pH, non-abrasive flow (more than two-thirds of the steel culverts inspected fit in this category). This was likely due to the superior galvanizing on the structural plate. If production methods could accommodate such a change, additional galvanizing would improve the performance of corrugated steel pipe installed in conditions which are predominant in Ohio.
- Because of the fine performance of unprotected (beyond galvanizing) structural plate pipe in high pH low abrasive flow areas, automatic use of one gage thicker bottom plates than structurally required (a practice now used by ODOT) should be discontinued.

c. Report No. 3

The third report consisted of a paper presented January 1984 by John Owen Hurd of the Ohio Department of Transportation at the

63rd Annual Meeting of the Transportation Research Board, Washington D.C.

i. Conclusions

The conclusions presented by the author were as follows:

"- Because of its limited service life (average years to poor of 3.16) bituminous coating of corrugated steel pipe culverts (AASHTO M-190 Type A) appears to be of little value.

- Bituminous coating with invert paving (AASHTOM 190 types B & C) extends the life of corrugated steel culverts for an average of 12 or more years depending on local conditions. An increase in the height of paving will extend the average service life.

- The main cause of loss of bituminous protection is loss of adherence rather than erosion of the material.

- Water pH and abrasiveness of flow are the only environmental factors which have a significant effect on the deterioration rate of corrugated steel pipe in Ohio.

- For high pH (>7.0) non-abrasive sites, plate pipe performance was significantly better than that of conventional corrugated steel pipe.

- Below a value of 7.0 water pH has a significant effect on the performance of concrete pipe.

d. Report No. 4

The fourth report consisted of a paper presented January 1985 by John Owen Hurd of the Ohio Department of Transportation at the 64th Annual Meeting of the Transportation Research Board, Washington D.C. This report concerned itself with the field performance of concrete pipe culverts at acidic flow sites in Ohio.

i. Conclusions

The conclusions were as follows:

"- Flow pH is the flow parameter with the greatest effect on concrete pipe performance at acidic sites in Ohio. More acidic flows cause more rapid deterioration.

- Increased pipe size and slope which are indications of flow volume and velocity accelerate any deterioration caused by acidic flows.

- Unprotected concrete pipe will provide a conservative service life in excess of 50 years for culverts with flow pH equal or greater than 4.5 in Ohio."

e. Report No. 5

The fifth report was prepared by Malcolm Pirnie Inc. dated April, 1985. It's primary objective was to evaluate the durability of bituminous-lined corrugated steel pipe storm sewers. A field survey of corrugated steel pipe storm sewers was conducted throughout the state of Ohio.

i. Conclusions

Their conclusions and recommendations were as follows:

- Full successful performance, defined as no linear or area loss of protection, was observed in 71% of all sections inspected. Successful performance, defined as linear or area loss of protection less than 10%, was observed in 90% of all sections inspected.
- The bituminous lining failed solely by loss of bond. Lining loss varied from 0% to 100% for the sections inspected.
- Bituminous lining performance appears to be unrelated to pipe segment location with respect to access point.
- Bituminous lining performance is related to 0.124 inch and one inch lining thicknesses. Poorer performance was noted for these thicknesses than for lining thicknesses from 0.25" to 0.75".
- Bituminous lining performance appears to be unrelated to depth of bury except for the no bury condition (open end sections) where change in temperature has a greater impact on the pipe.
- Bituminous lining bond failure occurred within less than eight years after installation.
- Bituminous lining performance in the sections inspected within the State of Ohio is related to manufacturer. Manufacturer No. 1 supplied the majority of installed bituminous lined corrugated steel pipe storm sewer. Nearly all observed "area loss" equal to or greater than 50 percent occurred in

pipe supplied by the Manufacturer No. 1 of record.

- Neither storm water pH nor flow abrasion were observed to affect bituminous lining performance.
- A significant number of deflection, alignment and related problems were observed during the inspection.
- No linear relationship existed between the number of sections having area loss and age.
- Manufacturers of bituminous-lined corrugated steel pipe storm sewers need to follow more rigid quality control practices.
- Bituminous protected pipe should not be exposed to severe weather after manufacture and before installation.
- A closer inspection by ODOT staff of corrugated metal pipe installations would reduce deflection and alignment problems.
- Protection thickness should be carefully checked for each pipe section supplied.
- Bituminous lined pipe sections should be evaluated again in another 5-10 years to determine the correlation between linear and area loss and age of pipe or installation.

ii. Recommendations

- Specifying agencies should prepare and test draft performance specification for the application of bituminous lining within corrugated steel pipe. Use accelerated testing procedures to evaluate the bituminous lining performance when the lining is installed in accordance with the draft performance specification.

- Limit bituminous lining thickness on corrugated steel pipe to Ø.25 inch minimum and Ø.75 maximum.
- Evaluate other coatings in lieu of bituminous lining (for example, laminates).
- ODOT should consider application of a repair field applied coating system on sections of pipe found to have lining losses so that protection of the pipe is restored.
- The precautions previously published by ODOT with respect to culvert design should also be considered with respect to storm sewer design for these parameters.
- An improved method of applying bituminous lining to corrugated steel pipe is needed to assure proper bond.
- Manufacturers of bituminous-lined corrugated steel pipe storm sewers need to follow more rigid quality control practices.
- Bituminous protected pipe should not be exposed to severe weather after manufacture and before installation.
- A closer inspection by ODOT staff of corrugated metal pipe installation would reduce deflection and

alignment problems.

- Protection thickness should be carefully checked for each pipe section supplied.
- Bituminous lined pipe sections should be evaluated again in another 5-10 years to determine the correlation between linear and area loss and age of pipe or installation.

11. Utah

a. Abstract

A Final Report[17] was submitted November 1974 to the Utah Department of Highways by Bob W. Welch. It was entitled "PIPE CORROSION AND PROTECTIVE COATINGS." Welch, in his abstract of the Report states as follows:

"Results indicate the total soluble salts is a more significant factor than any single soluble salt content in predicting pipe material performance. All soil sites examined eventually reached a soluble salt content of 0.8 percent. The corrosive effects of the solubles peak at approximately the 5 percent level. The effects of pH and minimum resistivity are found to be higher at the lower soluble salt content (<1.5%) and both lose their dominance at higher salt concentrations. Minimum resistivity, in particular, loses its effect on pipe life expectancies at a solubles content greater than 1.5 or 2 percent."

"The criterion used to predict performance correlates very well (a = Ø.Ø5 significance level) with field observations [and] varies only in areas beyond the limits of the selection criteria."

b. Conclusions

The Conclusions and Recommendations section of the Report states, in part, as follows:

"Metal structures subjected to potential aggressive attack from alkaline soils can be identified by knowing the soil characteristics of minimum resistivity, pH, and total soluble salts. By analyzing their combined effects, acceptable predictions can be made as to the steel's resistance to corrosion. At lower soluble salt contents the rate of corrosion is highly dependent on the minimum resistivity and pH whereas high salt contents will in themselves be the principal corrosive causing agent."

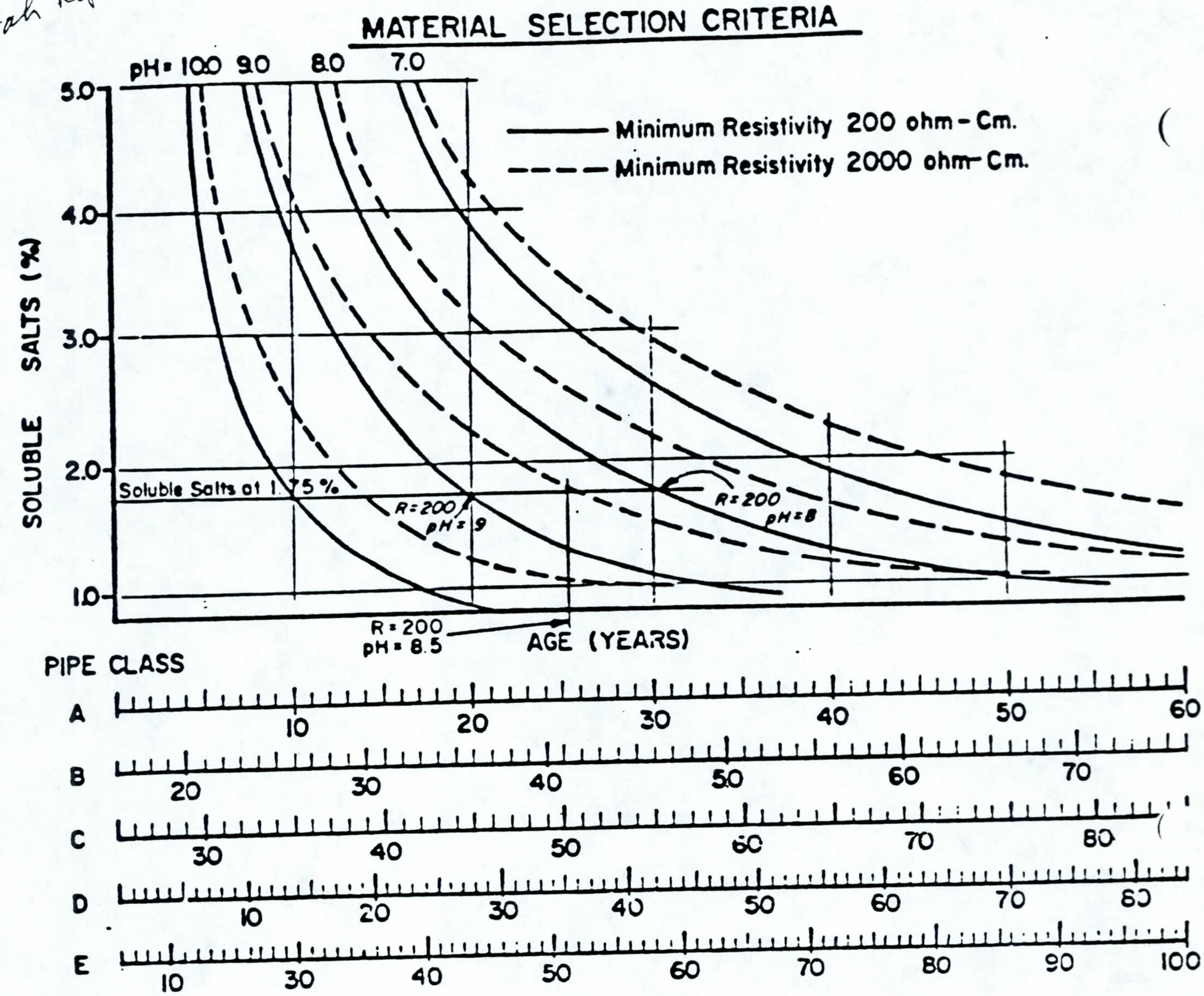
"Deterioration to concrete pipes also is highly dependent upon pH, soluble salts, and minimum resistivity in alkaline soil environments. However, the sulfate content, in amounts exceeding Ø.5 percent may be the principal deteriorating agent."

"Detailed research approach and evaluations have been included with indications the method of combining environmental [conditions] suspected of accelerating aggressive attacks on underground metal structures will yield similar results for acidic soil environments as for alkaline environments."

c. Charts

Welch presented two charts for Material Selection Criteria (Plate 8 and 9), as a means of predicting service life (age) versus the environmental conditions of total soluble salts, pH, and minimum resistivity. Plate 8 is for metal pipe with various coating alternatives, and Plate 9 is for concrete pipe.

Utah Report



Pipe Class A = Plain corrugated steel pipe.

Pipe Class B = Bituminous Coated Corrugated Steel Pipe, Aluminum Alloy Pipe, Galvalume Pipe, Pitch-Resin adhesive coated corrugated Steel Pipe (coated on outside only).

Pipe Class C = Asbestos Bonded Bituminous Coated Corrugated Steel Pipe, Pitch-Resin adhesive Coated Corrugated Steel Pipe (coated on Both sides).

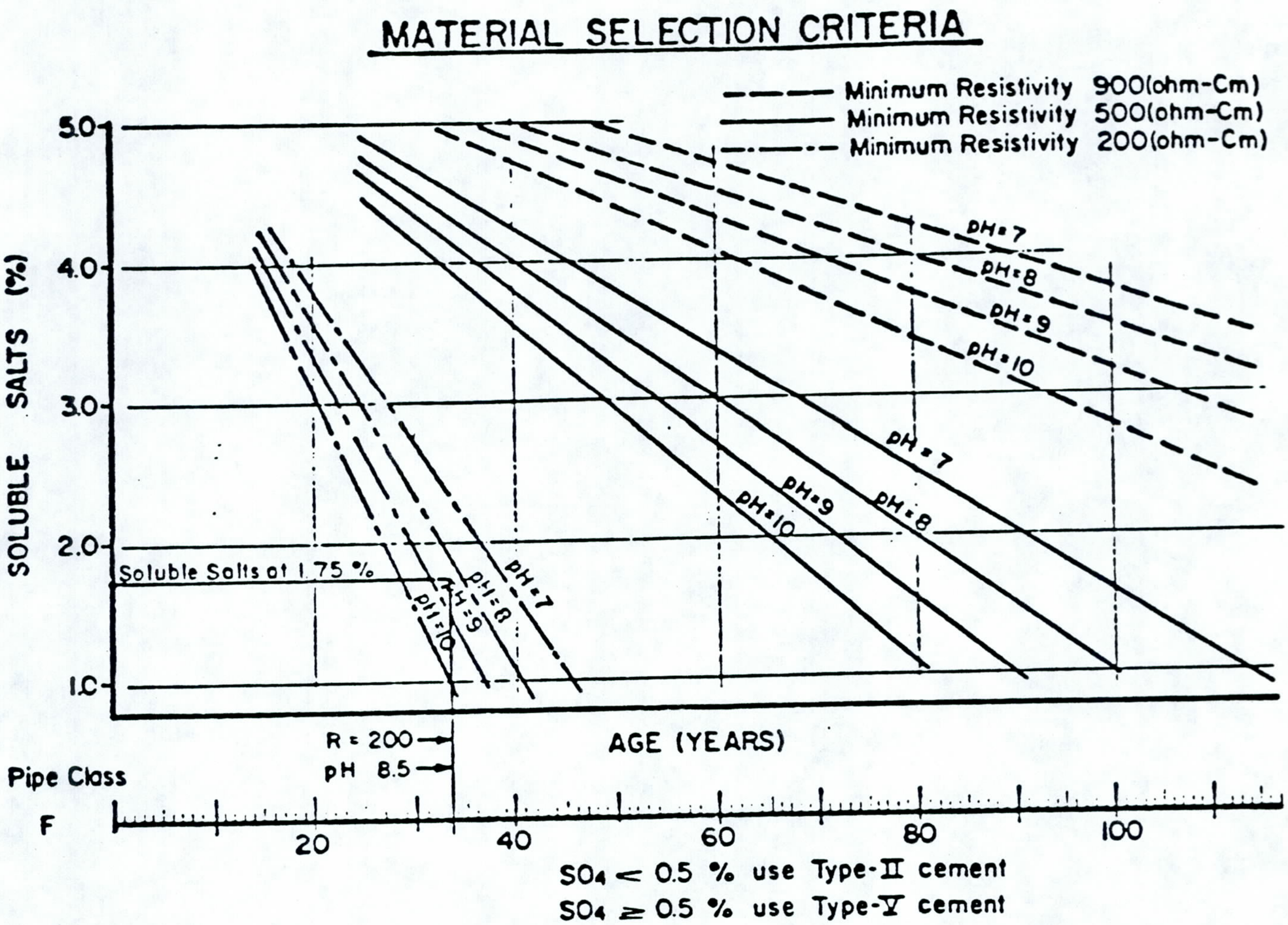
Pipe Class D = Plain Corrugated Steel Structural Plate Pipe.

Pipe Class E = Bituminous Coated Corrugated Steel Structural Plate Pipe, Aluminum Alloy Structural Plate Pipe.

NOTE: All Steel Pipes are Galvanized.

Figure 23

Utah Report



Pipe Class F = Portland Cement Concrete Pipe
Type-II Cement (SO_4 < 0.5 percent)
Type-V Cement (SO_4 ≥ 0.5 percent)

Figure 24

B. FEDERAL AGENCIES

1. Bureau of Public Roads

a. Introduction

In 1966 the Bureau of Public Roads (U.S. Department of Commerce) issued a Report[18] on Corrugated Metal Pipe Culverts, presenting Structural Design Criteria and Recommended Installation Practices. The introduction to this Report reads as follows:

"A design method is presented herein which takes into consideration the major factors that influence design and performance of corrugated metal pipe culverts. The factors take into account the many years of field experience with the performance of flexible culverts and the vast amount of research studies on buried flexible structures."

"Based on these factors, design criteria are presented in section 2, design, and a design chart has been prepared for each type of corrugation showing maximum permissible fill heights for each of the design criteria."

"Inasmuch as the adequacy of any pipe design can be nullified by poor installation practices such as lack of uniformity in pipe bed bearing, poor quality of side fill material, or lack of adequate compaction thereof, a section on installation practices is included which sets up basic installation requirements necessary to obtain satisfactory performance of pipe culverts."

b. Design

The section 2 design portion of the report develops the design formulae for determining allowable fill heights on corrugated metal culverts for three factors, namely deflection or flattening of pipe; critical buckling of pipe wall; and longitudinal seam strength. Deflection is computed by the Spangler formula, and allowable deflection is assumed to be 5 percent. If the pipe is elongated vertically by 5 percent [prior to backfill] a total deflection of 10 percent may be allowed, and the values of allowable height of backfill "h" doubled.

The report states "Values of E^1 (passive soil pressure), and "k" (soil stiffness coefficient), used in Criterion II are interdependent and are influenced by the quality of the side fill material and the degree of compaction (density) thereof. The design charts have been prepared on the basis of normal installation conditions, which require a value of 700 p.s.i. for E^1 with good side fill material compacted to 85 percent Proctor Density which is estimated to have a soil stiffness coefficient k = 0.44. The use of better quality side fill material with a greater degree of compaction will increase the value of E^1. Correspondingly the value of k will decrease in numerical value which means conversely a higher value of ultimate buckling stress, f_b. With excellent side fill material (graded gravel or crushed stone) compacted to 95-percent Proctor Density it is estimated that a value of E^1 = 1400 p.s.i. (and value of K = 0.22 may be used for special designs. Special designs shall be used only when the engineer is reasonably certain that requirements for excellent side fill material with 95-percent compaction can be met.

"All values of E^1 and k are estimated values based on results of research studies but further research is needed to correlate their values with various kinds of side fill material compacted to varying degrees of density."

"Failure of flexible pipe by deflection (decrease in vertical diameter) will not usually occur until deflection exceeds 18 to 20 percent below circular shape, consequently designs based on 5 percent will provide a factor of safety of at least 3.33."

[Comment - RGW. The Spangler formula was developed for use with the pipe to be installed under embankment conditions wherein the side fill material to at least one pipe diameter on either side of the pipe will be of known quality and compacted supposedly to a uniform density. However, storm drains are generally installed under trench conditions wherein there is no control over the suitability or natural density of the material immediately adjacent to the trench.]

The report then continues to develop formulae for the second and third criteria, namely; critical buckling of pipe wall; and longitudinal seam strength. The factor of safety for Criterion II is 2.0, and for Criterion III it is 3.33. Curves and charts were then prepared and appear in the report.

c. Handling and Installation Strength

Under Handling and Installation strength (2.8 on page 5) the report states as follows:

"... It is suggested that the deflection curves provide an approximate guide for increasing gages to maintain satisfactory stiffness. To use this guide, a heavier gage should be selected when the height of fill indicated by the deflection curves (5-percent deflection, no elongation) is 18.1 feet or less. This means that since the side fill will carry 17.1 feet of fill, the gage of pipe metal should be made heavy enough to carry better than one foot, making the total fill height 18.1 plus feet. Effect of elongation should not enter into this determination."

d. Durability

Under Durability of Corrugated Pipe (2.9 on page 5) the report recognizes that the service life of corrugated metal pipe may be seriously affected by corrosion and/or abrasion. It suggested a method of estimating service life of steel pipe as described in Highway Research Board Proceeding, 1962, "Field Test for Estimating the Service Life of Corrugated Metal Pipe Culverts", by J. L. Beaton and R.F. Stratfull, California Division of Highways (see Ref. 2, this report). Two other references were also cited. The report states: "Additional protection against corrosion may be obtained by the use of bituminous coatings (AASHO M-190), and paved inverts (AASHO M-190, type B or C) may be used as additional protection against abrasion. For structural plate pipe, heavier gages may be specified for the plates in the invert. Experience has shown that 16-gage metal in the lightest material that should be used to provide a reasonable service life."

The report further states: "For important installations where interruption of traffic would be undesirable or where the cost of replacement would be excessive, a minimum of 10-gage metal shall be used for steel structural plate and minimum of 0.15-inch thickness for aluminum structural plate."

[Comment - RGW. The report suggests that heavier gages may be specified for the plates in the invert as a protection against abrasion, but makes no mention of using a heavier gage metal for circular corrugated metal pipe to provide similar protection. Again in addressing the situation of important installations the report states that a minimum of 10-gage metal shall be used for steel structural plate and a minimum of 0.15-inch thickness for aluminum structural plate; however, no mention is made of the requirements for circular corrugated steel pipe. Is the inference to be made that the circular steel pipe should also use a minimum of 10-gage metal, or is the inference that circular pipe should not be used for those installation?]

e. Installation

In Section 3 Installation, the report discusses essential procedures in detail. Unfortunately the procedures are based upon installation of culverts, and not storm drains. Culverts are usually installed in an embankment condition, wherein embankment fill is placed over the pipe and above existing ground surface. Storm drains are usually installed in a trench condition below existing ground surface and with no fill above existing ground surface. The two conditions are quite different, particularly for satisfying side fill requirements. Under paragraph 3.5 side fill the reports states:

> "One of the most important phases of installation is the placing and compaction of side fill material (commonly called backfill) around the pipe. Side support must be provided for flexible pipe so that they will carry the fill and live loads without excessive deflection. Side support can only be obtained by adequate compaction of good fill material around the pipe. Side fill material within one pipe diameter of the sides of pipe and to one foot over the pipe shall be fine readily compactible soil or granular fill material. Side fill beyond the one pipe diameter limit at sides of pipe may be regular embankment fill."

[Comment - RGW - In culvert installation the contractor has control of the placing and compaction of the embankment - particularly within the one diameter limits stated above. For storm drain installations the trench width is generally kept to a minimum, being governed by the requirements for placing the pipe, completing the pipe joints, and placing and compacting the back fill around the lower one-half of the pipe. Very seldom would the width of the trench include the one-diameter width on either side of the pipe. The contractor has no control over the density of the natural soil outside the trench width, but within the one pipe diameter width required at specified density to provide the design value of passive earth resistance, E^1.]

Under this same Section 3.5 the report states as follows:

"Side fill material shall be placed as shown in Figure 3D in layers not exceeding 6 inches in depth and compacted at near optimum moisture content by approved hand or pneumatic tampers to the density required for superimposed embankment fill. Other approved compacting equipment may be used for side fill more than 3 feet from sides of pipe."

[Comment - RGW - It would be difficult to hold to the first part of this paragraph, i.e., "placed in layers not exceeding 6 inches in depth", yet it is obvious from the report that the success of the flexible pipe design theory that close and strict control of the backfill around the pipe is absolutely essential. The last sentence regarding backfill compaction equipment for side fill more than 3 feet from sides of pipe is in apparent conflict with a prior report requirement regarding backfill requirements up to one pipe diameter on each side of pipe for proper lateral support.]

The last sentence of the Section 3.5 reads as follows:

"Ponding or jetting of side fill should not be permitted."

[Comment - RGW - I agree with this statement of the report. The fundamental concept concerning the flexible pipe design theory depends upon a uniform lateral support for the pipe. I do not believe that ponding or jetting (including vibration agitation) accomplishes that requirement.]

2. Bureau of Public Roads

In 1970 the Bureau of Public Roads issued a second report[19] on corrugated metal pipe. It was, like the 1966 report, titled "Structural Design Criteria and Recommended Installation Practice".

The 1966 report was reported by Merrill Townsend, Structural Engineer for the bureau, while the 1970 report was reported by Erik W. Wolf, Structural Engineer, and Merrill Townsend, Consultant.

a. Forward

The "Forward" to the report generally repeats the "Introduction" to the 1966 report with the following additions:

"This publications updates and supersedes the 1966 BPR publication, "Corrugated Metal Pipe culverts." 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^1 from 700 to 1400 p.s.i. It has been found through experience and research that values previously used for soil modules E^1 were needlessly conservative. Present construction practice results in more uniform and reliable embankments which furnish improved soil support. The AASHO "Guide Specifications for Highway Construction" recommends 95 percent Proctor Density for roadway embankments. Soil modulus values E^1 are directly related to the quality of side fill material and the density to which it is compacted. E^1 values range from 700 p.s.i. for poor material at low density to more than 5,000 p.s.i. for select materials at normally specified densities which can be obtained by using bedding, side fill and compaction methods specified in this manual. Where these methods are not obtainable, the use of an E^1 value of 700 is recommended."

[Comment - RGW. This report, like the 1966 report, is basing its recommended values of E^1 on an embankment type of installation. For storm drains, under trench conditions, the similar values of uniform side fill compaction and hence E^1 values are very difficult to obtain, utilizing such methods as compacting in uniform 6-inch layers. Therefore I believe that the last sentence of the Forward (use of an E^1 value of 700 ...) should be the normal value in design of Phoenix storm sewers.]

b. Handling and Installation Strength

Under Sec. 2.4 Criterion IV - Handling and Installation Strength, the 1970 report presents a formula for a Flexibility Factor FF, and then states that:

"All diameter - thickness combinations shown in this manual, based on the design charts and the use of 120 lbs. per cubic feet for weight of compacted embankment, will result in Flexibility Factors not exceeding those given above."

c. Durability

In section 2.9 Durability of Corrugated Metal Pipe several new references were cited in addition to the one's cited in the 1966 report. In the fourth paragraph a sentence appearing in the 1966 report was deleted. The sentence read:

> "Experience has shown that 16-gage metal is the lightest material that should be used to provide a reasonable service life."

Also eliminated in the 1970 report was the following paragraph appearing in the 1966 report:

> "For important installations where interruption of traffic

would be undesirable or where the cost of replacement would be excessive, a minimum of 10-gage metal shall be used for steel structural plate and a minimum of 0.15-inch thickness for aluminum structural plate."

[Comment - RGW. It may be that the BPR felt that there was insufficient hard evidence to substantiate these statements. I believe these decisions can and should be made at the local agency level, based on local conditions.]

d. Installation

The Section 3 Installation in this report is essentially the same as in the 1966 report. One exception occurs in the last sentence of Section 3.5 Side fill. In the 1966 report it reads:

"Ponding or jetting of side fill should not be permitted."

In the 1970 report it reads:

"Ponding or jetting of side fill is not generally recommended."

e. Inspection

Section 3.11 Inspection reads as follows in both the 1966 and 1970 reports:

"Installation conditions have a very important effect on both the load on and the supporting strength of the pipe and a satisfactory installation requires attainment of design conditions in the field. Consequently, the engineer on the job should not only be familiar with good installation practices but should also keep a close check on the contractor's operations to insure fulfillment of that objective."

[Comment - RGW. The fulfillment of the objective depends upon the capability of the manufacturer to meet the requirements (tightness) of the specifications, and the capability of the inspectors, at the manufacturing plant and at the site of installation, to insure that the specifications are being adhered to. It is sometimes better to use a more conservative design with less stringent spec requirements, based upon what can logically be assumed is attainable in the shop and in the field (See the following comment from the 1970 report.]

f. Design Charts and Recommended Fill Heights (Precaution)

In Section 4: Design Charts and Recommended Fill Height Tables, the closing paragraph reads as follows:

"It is again emphasized that these design charts and tables are predicated on obtaining, in the field, the quality of side fill material and compaction that are specified in Section 3, Installation, and upon the use of the above basic data. i.e. Where the degree of inspection and quality and compaction of side fill material obtainable on the site are such as to make it doubtful whether the above installation requirements can be met, fill heights should be calculated from design charts and formulas based on values of $E^1 = 700$ and $k = 0.44$.

3. Federal Highway Administration

The FHWA issued a Technical Advisory T5040.12 dated October 22, 1979.[20] The subject of the TA was "Corrugated Metal Pipe Durability

Guidelines". The following excerpts were taken from the TA.

"a. Background

i. In order to specify and take bids on alternate materials, the designer must make a determination that two or more products or materials are equal in their ability to perform their intended function for the design life of the project. The Federal Highway Administration (FHWA) has for some years required the states to specify alternate materials for some culvert, underdrain, and storm drain applications. (See Federal-Aid Highway Program Manual, Volume 6, Chapter 4, Section 1, sub-section 16, paragraph 7d, General Material Requirements).

ii. The structural design of corrugated metal pipe is given in detail in the current American Association of State Highway and Transportation Officials (AASHTO) specifications; construction and installation are also covered. The hydraulic design is covered in an AASHTO guideline. Almost all states use these AASHTO documents as published or as modified to satisfy their particular requirements. However, there is no AASHTO guidance, and prior to the initial issuance of this TA, no FHWA guidance on estimation of service life relative to the various environmental factors which come into play during the lifetime of a drainage structure.

iii. The FHWA alternate [bids] requirement plus the competitive forces in the marketplace have forced the states to establish acceptable conditions under which the various culvert materials may be used. These "acceptable conditions" vary widely among the states. Many states have conducted research programs to determine how metal culverts are performing in the field and what environmental factors affect performance and to what degree. As a result of this research some states have developed rational design methods of durability. Other states have simply observed culvert performance and have established durability equivalence based on these observation."

"b. Discussion

i. The use of bituminous paved invert to minimize the effects of abrasion has been questioned by some agencies; however, most still credit some added service life value to this type of abrasion protection. Local experience with bituminous paved invert should be considered in making the evaluation of this treatment."

"c. Guidelines

i. General. The following guidance is offered relative to designing for durability and for help in determining the suitability of galvanized steel and aluminum alloy corrugated metal pipe. It is pointed out that any reference to specific service life in terms of years is absent, primarily because drainage structure design engineers have been unable to agree on a definition of pipe failure and on what service life should be provided. Some engineers design on the basis of time to first perforation; others calculate time to reduce the structural safety factor to one. Regardless of the method used to determine estimated service life, it should be recognized that the result is still an estimate and not an absolute value.

ii. Galvanized Steel.

- Bare (uncoated) galvanized steel pipe generally performs well when the pH of the soil immediately adjacent to the pipe and the pH of the flow which the pipe will carry are between 6 and 10 and when the electrical resistivity of the flow and the minimum electrical resistivity of the soil are 2,000 ohm-cm or greater. For very low pH and very high pH, there appears to be a direct relationship to resistivity and metal wastage. It is suggested that galvanized steel performs well down to a pH of 5 and up to a pH of 12 at soil and water resistivities above 10,000 ohm-cm.
- There is some service life data indicating that uncoated galvanized steel pipe can render satisfactory service when embedded in soils with minimum resistivities as low as 2,000 ohm-cm when the pH is between 7 and 10.
- Galvanized steel pipe should not be used in salt or brackish, environments except when the pipe is asbestos bonded with a bituminous coating and a paved invert.

- Pipe installed at sites that are considered to be substantially abrasive should be bituminous coated with paved invert (see paragraph 4e); at severely abrasive sites some type of special treatment should be considered.
- The paving of the invert of bituminous coated steel pipe has been done primarily to reduce the effects of abrasion. There is some evidence that the paving of the invert also will significantly prolong culvert life by preventing corrosion, as well as abrasion, of the invert.
- Polymeric Coatings.
  - The corrugated steel pipe industry has developed several polymeric coatings for galvanized steel pipe. Laboratory test data and a limited amount of field data indicate that these coatings provide, at least, the degree of protection presently provided by bituminous coating. These polymeric coatings are applied by laminating or roller coating to a galvanized surface properly cleaned and prepared to receive the coating in contrast to the usually unprepared surface to which a standard bituminous coating is applied.
  - Polymeric coatings on galvanized steel pipe have been field tested on pipe carrying very acid run off. Observations of these pipes generally

indicate that the coating itself is not affected and where it has retained its bond to the pipe, the galvanized steel substrate is also not affected. Some delamination has occurred, usually at or near a spiral lock-seam indicating that the delamination is a direct result of faulty pipe fabrication.

- The experimental use of pipe with these coatings is encouraged so as to develop additional service life date. The AASHTO Material Specifications M-245 and M-246 describe the pipe, the coatings, and the galvanized steel sheet for polymeric coated steel pipe.

iii. Aluminum Alloy

- Bare (uncoated) aluminum alloy pipe generally performs well when the pH of the soil immediately adjacent to the pipe and the pH of the flow which the pipe will carry are between 4 and 9, and when the electrical resistivity of the flow and minimum electrical resistivity of the soil are 500 ohm-cm or greater. Uncoated aluminum alloy pipe, when backfilled with a clean granular well draining soil, has shown excellent resistance to corrosion when exposed to sea water and tidal flow even though seawater resistivity averages around 35 ohm-cm.

- Pipe installed at sites that are considered to be substantially abrasive should be bituminous coated with paved invert. At severely abrasive sites the use of aluminum pipe is not recommended.

d. Closure

- The acceptable limits of pH and resistivity suggested in Table I (Plate 10) ... and Table II (Plate 11) ..., are based on 0.064-inch thick steel and 0.060-inch thick aluminum. Increasing metal thickness is one way to increase life expectancy. It also may be used to permit use in environments outside the limits suggested when data are available to warrant such use. Generally, the rate of corrosion of steel pipe remains constant; therefore the increase in life expectancy is proportional to metal thickness. The rate of corrosion of aluminum pipe generally tends to slow with the passage of time, particularly with alclad alloys. However, not enough data are available to determine the precise relationship between corrosion rate reduction and time.
- It is realized that pH and resistivity are not the only environmental factors associated with culvert corrosion. Some researchers have suggested sulfate and chloride content of the soil, degree of permeability of the soil, presence of organic matter, and water hardness as being significant, but most agree that pH and resistivity are important and relatively easy to determine. Polarization

(7) See Table I for a summary of these guidelines.

Table I
GALVANIZED STEEL CORRUGATED METAL PIPE

Type of Steel Pipe Listed In Order of Ascending Degree of Durability	Pipe Fabrication Per AASHTO Specification	Soil & Water pH Min - Max	Soil & Water Resistivity(1) Min ohm-cm	Abrasion Rating(2) Max
Galvanized Steel Uncoated	M-36 M-167	6 - 10 5-6 & 10-12	3,000 10,000	Mild
Galvanized Steel Bituminous Coated	M-36 & M-190 M-167 & M-243	5 - 12	3,000	Moderate
Galvanized Steel Bituminous Coated with Paved Invert	M-36 & M-190	5 - 12 4 - 5	3,000 10,000	Substantial
Galvanized Steel Asbestos Bonded with Bituminous Coating and Paved Invert	Federal Spec. WW-P-405B(4)	4 - 12	1,000(3)	Substantial

(1) Minimum soil resistivity determined in the lab from a soil sample.

(2) Abrasion ratings - Mild
Moderate
Substantial
Severe

(3) Does not apply to salt or brackish water when pipe is buried in clean, well-draining soil.

(4) There is no AASHTO specification for this coating.

c. Aluminum Alloy

(1) Bare (uncoated) aluminum alloy pipe generally performs well when the pH of the soil immediately adjacent to the pipe and the pH of the flow which the pipe will carry are between 4 and 9, and when the electrical resistivity of the flow and minimum electrical resistivity of the soil are 500 ohm-cm or greater. Uncoated aluminum alloy pipe, when backfilled with a clean granular well

draining soil, has shown excellent resistance to corrosion when exposed to seawater and tidal flow even though seawater resistivity averages around 35 ohm-cm.

(2) Pipe installed at sites that are considered to be substantially abrasive should be bituminous coated with paved invert. At severely abrasive sites the use of aluminum pipe is not recommended.

(3) See Table II for a summary of these guidelines.

Table II
ALUMINUM ALLOY CORRUGATED METAL PIPE

Type of Aluminum Pipe Listed In Order of Ascending Degree of Durability	Pipe Fabrication Per AASHTO Specification	Soil & Water pH Min - Max	Soil & Water Resistivity(1) Min ohm-cm	Abrasion Rating(2) Max
Aluminum Alloy Uncoated	M-196(4) M-219	4 - 9	500(3)	Moderate
Aluminum Alloy Bituminous Coated	M-196(4) & M-190 M-219 & M-243	4 - 9	500(3)	Moderate
Aluminum Alloy Bituminous Coated with Paved Invert	M-196 & M-190	4 - 10	500(3)	Substantial

(1) Minimum soil resistivity determinded in the lab from a soil sample.

(2) Abrasion ratings - Mild
Moderate
Substantial
Severe

(3) Does not apply to salt or brackish water when pipe is buried in clean, well-draining soil.

(4) Aluminum alloy alclad 3004-H34 per ASTM B-209.

6. CLOSURE

a. The acceptable limits of pH and resistivity suggested in Table I for bare galvanized steel and Table II for bare aluminum alloy, are based on 0.064-inch thick steel and 0.060-inch thick aluminum. Increasing metal tests can be useful for comparing potential corrosion rates of different sites and different materials.

- A single nationwide design method is not possible at this time. The intent of this TA is to indicate, generally, the conditions under which field data have shown that these materials have performed satisfactorily. The lack of an acceptable definition of failure and any reference to actual years of life means that engineers should examine their own experiences and those of others so as to arrive at the best informed decision possible."

4. Federal Highway Administration

The FHWA issued a Final Report[21] dated June 1980 titled "Evaluation of Highway Culvert Coating Performance." The following are excerpts from that report.

a. "Summary

"Field inspections at 82 locations in 9 states indicate that most coatings are effective in situations where runoff does not include abrasive debris and the water does not contain a high percentage of soluble salts, particularly chlorides. All organic coatings inspected are subject to impact and abrasion deterioration and most will deteriorate under wet alkali or salt conditions. Low pH conditions do not seem to deteriorate the coating as much as attacking the metal substrate of coating defects, causing disbondment. The best all around existing coating system is asbestos bonded asphalt coated and paved galvanized steel."

"The most commonly used coating, asphalt, suffers from poor adhesion under immersion conditions, low impact strength at low temperatures and water penetration leading to removal from the substrate. Less than adequate surface preparation prior to coating and ill-defined application techniques impair this coating's performance. Possible improvements to this coating include the use of organic additives to improve adhesion and blending with other components such as inorganic fibers or organic polymers to improve mechanical properties."

"Alternate coating systems might prove beneficial for protecting culverts. Coating systems include urethanes, epoxies, neoprene, fusion bonded coatings, ceramics, and metalized coatings. While these coatings are more costly than any current culvert coating, they have the advantage that they can be applied only where needed, such as on the invert. Additional study is desirable to identify the most cost effective coatings."

"Several primers and wash primers were evaluated in laboratory screening tests to determine if improvements in the adhesion of asphalt and other coatings to galvanized steel can be obtained. The tests show that some adhesion improvement is possible but that further work is needed to establish the cost effectiveness of primers under culvert exposure conditions." ....

b. "Introduction

Increasing metal thickness to compensate for expected corrosion and erosion losses is a method of increasing the life expectancy of culverts. The degree of expected corrosion and/or erosion must be known for the site involved. Severe corrosion or erosion limit the applicability of this method making other methods more cost effective for a particular situation."

"Materials known to be desirable in severe environments can be used in place of coatings or other measures. These materials include: aluminum, concrete, vitrified clay, stainless steel, polymers and fiberglass."

c. "Field Investigation

i. Asphalt .....

Six states have discontinued the use of asphalt coating, they are: Hawaii, Kansas, Maryland, Missouri, Pennsylvania and Tennessee. Asphalt is no longer used because it was found to provide an insufficient increase in service life to justify the cost. Poor service life in these states was the result of abrasion and impact failure. Two of these states, Missouri and Pennsylvania are using the organic coatings (polymerics); the others are of the opinion that organic coatings are unnecessary and that substitute materials, such as concrete, can be used in corrosive situations."

"ii. Asphalt Coated Aluminum

Inspections included only four asphalt coated aluminum culverts (two at test sites). .... Coatings on both aluminum culverts examined in field use were in good condition with little coating deterioration and no corrosion of the aluminum. Abrasion and rapid stream flows did not appear to be factors in the two culverts examined. Asphalt exhibits a poor bond to aluminum, being easily removed by prying. ......"

"The sample size is too small to make firm conclusions but it appears that asphalt coated aluminum is unsuitable for abrasive locations. We do not know how paved aluminum would perform but suspect it would not perform as well as asphalt paved galvanized steel."

"iii. Asbestos Bonded Asphalt Coated Galvanized Steel

Asbestos bonded asphalt coated galvanized steel generally exhibited better performance than plain asphalt dipped galvanized steel. This coating is still subject to the same modes of deterioration as asphalt coated pipe, that is: checking and cracking at exposed ends and abrasion of the invert."

"iv. Coal Tar Laminate

Coal tar laminate (U.S. Steel Nexon) exhibits good performance except under abrasive stream flows and in low pH and high salt environments."

[Comment - RGW. Culverts inspected contained a defect in the lock seam caused during the lock seam forming period. The coating is cut through to the base metal by the tooling process. This creates a path permitting rapid deterioration.]

"v. Polyethylene (Inland Black Clad)"

[Extensive general blistering and disbonding found at several sites.]

"vi. Polyvinyl Chloride (Plasti-Cote)"

[Results similar to polyethylene].

"vii.Epoxy Coated Concrete"

[Seemed to be successful in protecting the concrete substrate]

viii.Others

- Vinyl plastisol coating (Bethlehem Steel Beth-cu-loy-pc).

  [Observed abrasive damage much less than a companion coal tar laminate. However erosion had occurred, affecting upstream sides of the culvert crests.]

- Granite paving

  [Unsatisfactory in acidic flows. Also breaks loose from the corrugated steel]

- Concrete paving over asphalt paving over asbestos bonded.

  [Concrete was eroding severely, and water was flowing under the concrete.]

- Concrete paving over asbestos bonded asphalt.

  [Concrete probably reinforced per Utah specs. No deterioration - however, culvert experiences only intermittent flow.]

- Vitreous clay lined concrete.

  [1 sample observed only - appears to perform satisfactorily. No erosion of clay plates, some erosion of mortar after 18 years.]

- Aluminized steel.

  [1 sample observed only. In alkali soil at Utah test site. Some deterioration at the spiral weld and some corrosion to the soil-air interface [culvert exit?].

- Aluminum-zinc(Bethlehem Steel Galvalum)

  [1 case examined-paired with galvanized culvert. On interior both coatings have completely deteriorated. Exterior of galvelum culvert is deteriorating more rapidly than that of the galvanized culvert. (Galvalum practically depleted while galvanizing is intact)]

- Epoxy coating, organic zinc coating, and inorganic zinc coating examined at Utah Test Site. All completely deteriorated in an alkali soil.

- Unbonded polyethyline wrap" - [unsatisfactory]

5. Corps of Engineers

   a. General

   In November 1974 the Corps of Engineers issued a Final Report[23] "Corrugated Metal Pipe Study". The report was prepared by Curtis L. Craig, under contract.

   The summary of the report indicated that the investigation included inspection of the condition of nine corrugated metal outlet conduits approximately 10 years after construction. The interiors were examined and measurements made of pipe to remote soil potentials, and these formed the basis of evaluation.

   The investigation found peeling of the hot-dipped asphalt coating was prevalent. In many cases the remaining asphalt was brittle and could be easily and cleanly removed from the pipe. Soil resistivity measures made in place showed a range of

100-2000 ohm-cm, consistent with a severe degree of corrosion activity.

b. Recommendations

The recommendations (in the summary) included the following:

- that corrugated metal pipe not be used for future outlet conduits became of poor joints and the uncertainty of the corrosion protection of the asphalt coating;
- that an interior lining be constructed within existing CMP conduits, and
- that construction of design durability charts based on soil resistivity and hydrogen ion activity does not appear to be feasible.

c. Discussion

The above recommendations also appear at the conclusion of the report. An interesting discussion was provided in Section 5.0 COATINGS FOR UNDERGROUND STRUCTURES. Reference is made to many publications published by the National Association of Corrosion Engineers, noting that the information is based on studies involving pipelines rather than outlet structures [or culverts]. The report lists the desirable properties that a coating should have, as follows:

"- Sufficient electrolytic resistance to resist the electrolyte, that is, the solution of soil chemicals in the ground water, from contact with the metal;
- Resistance to moisture penetration and solubility;

- Insolubility in soil contaminants as well as ground water, if there is a risk of such contamination from such things as oil spills;
- Elasticity sufficient to resist cracking during installation or from changes in loading during service;
- Stability, that is, not suffer loss of plasticizing oils during heating for application, or by leaching during service;
- Sufficient hardness to resist penetration by rocks and other hard objects in the backfill;
- Resistance to changes in hardness or penetration that can occur with changes that may occur during installation or during service;
- Resistance to stresses from settlement or shifting of the soil; and
- Inertness to bacterial deterioration."

d. Pipeline Coatings

The report lists seven kinds of materials that have been used for pipeline coatings. These are as follows:

"i. Coal Tar Enamel

ii. Asphalt Enamel

iii. Asphalt Mastic

iv. Tapes

v. Extruded polyethylene or polypropylene

vi. Thin film organic coatings

vii. Microcrystalline wax."

The report states:

"The systems that best satisfy the list of desirable properties are the coal tar enamels, system 1, and thin film organic coatings (usually based on epoxy resins), system 6."

"Descriptions, applications and some precautions are provided in Exhibit G." Exhibit G follows herein.

EXHIBIT G

PROTECTIVE COATINGS FOR BURIED STRUCTURES

Coating System	How Applied	Remarks
1. Coal Tar Enamel. Pitch, a by-product of the manufacture of coke from soft coal, and of low sulfur content, is distilled until the desired softening point and penetration are obtained. Fillers such as talc, mica, or blue-black slate flour are added to the pitch. Plasticized enamels are obtained by adding powered soft, coal and heavy oils before adding the filter.	Metal is cleaned by sand or metal grit blast or by power brushes. Primer which is pitch in a solvent such as naphtha is applied to the clean metal. The primer wets the metal surface and then blends with the enamel. Enamel is applied hot by mopping. If the metal were not primed, the enamel would chill too fast for proper bond. Usual thickness is 3/32". To overcome soil stresses, wrappings of cloth fabrics, burlap, jute, asbestos felt, impregnated glass fiber tapes, etc. are then applied.	Relatively inexpensive and has a long history of good service. Noxious fumes occur during application. Subject to cold flow (sagging) if time between coating and installation is too long.
2. Asphalt Enamel. Pitch is a by-product from oil refineries, the asphalt residue being about 3% of the crude oil before refining. Stock is selected having a minimum of free carbon, low salt content, and low in wax, grease, and oils. Stock is blown with air at 465 deg. to 490 deg. F. for 10-12 hours softening the stock filler of blue-black slate flour, 95% passing through 325 mesh screen added	Cleaned metal is primed with an enamel stock to which solvents and special ingredients are added. Thicknesses of about 3/32" are applied hot by brush, dip or spray methods. Except for very minimum protection such as short required life or locations known not to be corrosive, wrapping is applied to prevent coating damage by handling or soil stresses. Automatic machines which combine all application	More variable in composition than coal tar. Less expensive than coal tar. May deteriorate more rapidly. Researchers have found evidence of microbial attack on asphaltness, resins, and maltenes added to insure desirable properties.

Coating System	How Applied	Remarks
without further heating to produce the final enamel. Specified controls are usually softening point, penetration (before and after heating) and weight loss on heating.	processes from cleaning the metal to wrapping have been used in both shops and "over the ditch" applications.	
3. Asphalt Mastic. An aggregate of fine gravel, sand, and limestone in a binder (approximately 4% by volume) of asphalt.	Metal is cleaned and primed as above, then mastic is applied by trowel or machine.	Furnishes excellent long term protection. Moderately expensive. May suffer some microbiological attack.
4. Tapes. Polyethylene, polyvinyl chloride, coal tar with glass fiber reinforcement, etc., some with butyl rubber mastic inner layer.	Metal is cleaned and, for some tapes, a liquid primer applied. Pressure sensitive adhesives permit hand or machine wrapping, usually layers overlap by half.	Tend to disbond. Water ingress may occur at over laps which may be traced to microbial attack on the adhesive.
5. Extruded polyethylene or polypropolene.	Plastic is extruded onto clean metal as it passes through a special machine.	Special care needed at pipe joints. Plastic sleeves are available which can be slipped over the joints and heated to shrink into place.
6. Thin film organic coatings. Many polymeric and resinous organic materials are feasible, but those based on epoxy resins have been most widely used.	Metal must be scrupulously clean. Can be applied by most any method, including brush, spray, dip, roller, fluidized bed, electrostatic spraying, flame spraying, and electrocoating.	Mechanically tough and have good chemical as well as high electrical resistance. Special care needed at joints. Some coatings are subject to water ingress under plastic film and/or water permeation through coating.
7. Microcrystalline Wax.	Sprayed hot onto clean metal. Reinforced by an outer layer of polyvinylidene chloride (Saran).	Expensive. Relatively easily indented. Excellent adhesion to pipe, which can be bent without damage to bond between coating and pipe.

6. National Bureau of Standards

a. Field Tests

In April 1957 the National Bureau of Standards (NBS) issued circular 579,[24] prepared by Melvin Romanoff. The subject of the circular was underground corrosion. Section 16 was concerned with "Behavior of Metallic Coatings in Soils". Several coating types were included, namely zinc, lead, aluminum, and tin. The results of the field tests on galvanized coatings was reported on page 110 as follows:

> "In 1924, an underground exposure test was initiated on a series of five different base metals (Bessemer steel, wrought iron, plain and copper-bearing steel, and open-hearth iron) to which a series of zinc coatings were applied by the hot-dip process. This test was terminated after 10-years exposure. An analysis of these data showed that in most of the soils, zinc coating of 2 oz. or less were destroyed during the 10-year exposure period, and pitting of the underlying steel occurred. However, the test showed that the 3-oz. coatings were intact on at least half of the specimens, and in only one (soil 23) of the 47 soils was there any measurable development of pits in the steel. Although the galvanized specimens differed somewhat in coating weight and uniformity of thickness, the results of the tests show in the case of the five alloys tested, that the base metal is not a factor in the corrosion rate."

b. Bituminous Coatings Tests

In Section 18 bituminous coatings were evaluated. Field tests were conducted by the NBS, by NBS in cooperation with the American Gas Association (AGA), and by NBS in cooperation with the American Petroleum Institute (API).

i. NBS/AGA Tests

The NBS conducted field tests on several types of bituminous coatings applied by the coating manufacturers to sandblasted 2-inch steel pipe. three inspections were made, the last one in 1934 after the coatings had been exposed for about 5.5 years. The results were summarized as follows:

"- that none of the coatings prevented corrosion entirely at all test sites,

- that coal-tar base materials were more table and waterproof than asphalt-base materials,

- that machine-applied coatings were superior to hand-applied coatings and particularly to hand applications in the field, and

- that any organic reinforcement in a coating is a weakness, especially if the coating is asphalt.

ii. NBS/API Tests

The NBS-API tests were primarily demonstrations of the relative behavior of certain proprietary coatings. The test program was begun in 1930. The following items were presented as facts established by the test.

"- Many of these coatings will greatly reduce corrosion during at least 10 years, (the period of this test), although complete protection from all corrosion has not been realized in corrosive and destructive soils.

- The effectiveness of all coatings tested decreased throughout the period of the test. This in most cases is the result of continued soil pressure and the absorption of water. There appears to be little change in the coating materials other than that in the organic fabrics used as reinforcements or shields.
- Shields and reinforcements should be permanent and sufficiently rigid to distribute soil stress and pressure due to the weight of the pipe over enough area to prevent the flow of the bituminous or other material in the coating.
- In these particular tests, the thicker coatings appeared to provide better protection.
- A coating should be sufficiently rigid to withstand pressures over long periods and elastic enough to withstand stresses resulting from pipe movement and sudden changes in temperature. These requirements are difficult to obtain in any one coating.
- A coating that develops flaws at one or more points may cause deeper pits at those points than would have occurred on uncoated pipe in the same location.
- In mildly corrosive soils, no protective coating is required unless the cost of a leak would be abnormally

high.

- These tests show that comparable results are obtained from exposures of isolated short sections of coated pipe and from long sections of pipelines.
- The presence of uncoated or bare sections in a coated pipeline did not appreciably affect the pit depth-time relation for the adjacent coated sections."

7. Soil Conservation Service

a. Excerpts

Howard W. Hall, Soils Engineer with the SCS, reported, in September 1978[25] on a survey performed on corrugated steel pipe spillways and outlet structures in Iowa, Kansas, Missouri and Nebraska. Although the installations are not similar to storm chain installations, some excerpts are included hereinbelow.

page 2

"PIPE PERFORMANCE RELATED TO SOIL RESISTIVITY"

Resistivity and pH of the foundation and backfill soil is used in the SCS to determine the need for cathodic protection on corrugated steel pipes. When saturated soil resistivity is less than 4000 ohm-cm, or pH less than 5.0 SCS technical guides require cathodic protection.

page 10

"Asphalt coatings usually do not stay on the invert of wet pipes. Asbestos bonding is of some benefit in keeping asphalt coating on the pipe interior."

"ASPHALT PAVING

Some of the pipes inspected had asphalt paving in the invert. In virtually all cases the paving had been partially to almost completely removed by flowing water and was no longer performing its intended function."

"The pavings had discontinuities at pipe joints. It appeared turbulence created at these discontinuities was also instrumental in stripping paving from the pipes."

Page 11

b. "Conclusions

i. Corrugated steel pipes have performed satisfactorily in many SCS designed installations for more than 25 years and are still in good condition.

ii. Some pipes have failed by corrosion in a relatively short time (5-15 years).

iii. Soil resistivity greater than 4000 ohms-cm indicates a lower corrosion rate for pipes than soil with lower resistivity, but does not guarantee satisfactory performance.

iv. Asphalt coated pipe and bonded and coated pipes can be expected to have a longer life than uncoated pipes.

v. Corrosion on the inside of pipes due to standing and running water is a major contributor to failure in many locations.

vi. The corrosion rate on the inside of pipes with running or standing water is lower on asbestos bonded and coated pipes than for asphalt coated or uncoated pipes.

vii. Most corrugated steel pipes leak. The leaks cause wetting of the pipe interior and, in some cases, contributes to interior corrosion. It may contribute to ice build up in winter.

viii. Asphalt coatings on the inside of pipes is stripped out by high velocity flows. Asphalt coatings on asbestos bonded pipes are more resistant to flows than those on unbonded pipes.

ix. Asphalt pavings are stripped out by high velocity flows."

c. "Recommendations

i. Use asphalt or other approved coatings on all corrugated steel pipe except (a) temporary installations, (b) experience in similar soil and moisture conditions in the area indicates a justifiable economic life for uncoated pipe, (c) the soil resistivity exceeds 4000 ohm-cm, the pH is 5.0 or greater and there is no experience in the area that indicates an unusually corrosive condition, or (d) replacement is relatively easy or low cost such as a small pipe with shallow cover.

ii. Do not consider corrugated steel pipe to be watertight. Do emphasize the careful assembly and tightening of bonds to produce as tight a pipe as possible.

iii. Do not use paved inverts on pipes designed for pressure flow (drop inlets or hooded inlets). If paved inverts are required, design the pipe to assure channel flow.

iv. Design pipe grades to avoid ponding of water in a pipe whenever site conditions permit. This includes a positive pipe grade after foundation settlement and a free draining outlet.

v. Backfill pipes with the least corrosive soil available that meets other backfill requirements. This includes highest resistivity, neutral pH, and freedom from organic matter. As nearly as possible, use the same soil material for all backfill including undercutting the pipe grade and placing at least one foot of backfill beneath the pipe.

vi. Carry out studies and trials to develop methods to identify critical conditions and control corrosion of pipe interiors."

C. COUNTY AND CITY AGENCIES

1. Los Angeles County, California

In January 1973 a report[26] was submitted in draft form to the Los Angeles County Flood Control district titled "Corrugated Steel Pipe for Storm Drains" by Smith, R. J. and Vita, L. A. As of November 1986 the report has not been released for publication and the district has no plans to publish the report. The district declined to give permission to quote any information contained in the draft report (per telephone conversation with Dan Short of the District staff).

2. City of Phoenix, Arizona

In July 1958 a report[27] was submitted to the City of Phoenix by Frank Buck, Consulting Engineer, titled "Storm Drain Corrosion Study". The objective of the study was a soil resistivity survey and external corrosion study for a proposed 19th Avenue storm drain.

The route of the proposed storm drain was along 19th Avenue from the Grand Canal (north of Indian School Road) to a point 500 feet south of Durango, then west to 22nd Avenue, then south approximately one mile to the Salt River. Soil resistivity tests were made at 5 feet, 10 feet, and 15 feet soil depth along the route as shown on the enclosed map. The report states in part as follows:

"The soil resistivity tests made along the proposed storm drain route were almost without exception indicative of corrosion possibilities. By observing the data and the histogram of the tests, one can observe that generally the soil resistivity tests made to an average depth of 5' are the most corrosive. And it is this layer of soil that the proposed storm drain will have to occupy. The histogram shows that about 30% at 5' and 6% at 10' of the tests measured 1,000 ohm-cm or less. For the range between 1,000 and 3,000 ohm-cm the percentages were 41, 71, and 76 for the 5', 10', and 15' tests respectively."

"There is little question but that this soil, due to its low resistivity, would be corrosive."

"The 5' average depth graph indicates the lowest resistance is between McDowell Road and Van Buren Street. Three consecutive tests showed soil resistances of 730 ohm-cm, 480 ohm-cm, and 650 ohm-cm respectively."

"This portion of the route was also low on the 10' tests and was near the low on the 15' tests."

"The corrosiveness of the soil can be determined by the low resistivity and the slope of the line connecting adjacent resistivity readings. The lower the reading and the steeper the slope are generally conditions for corrosion attack."

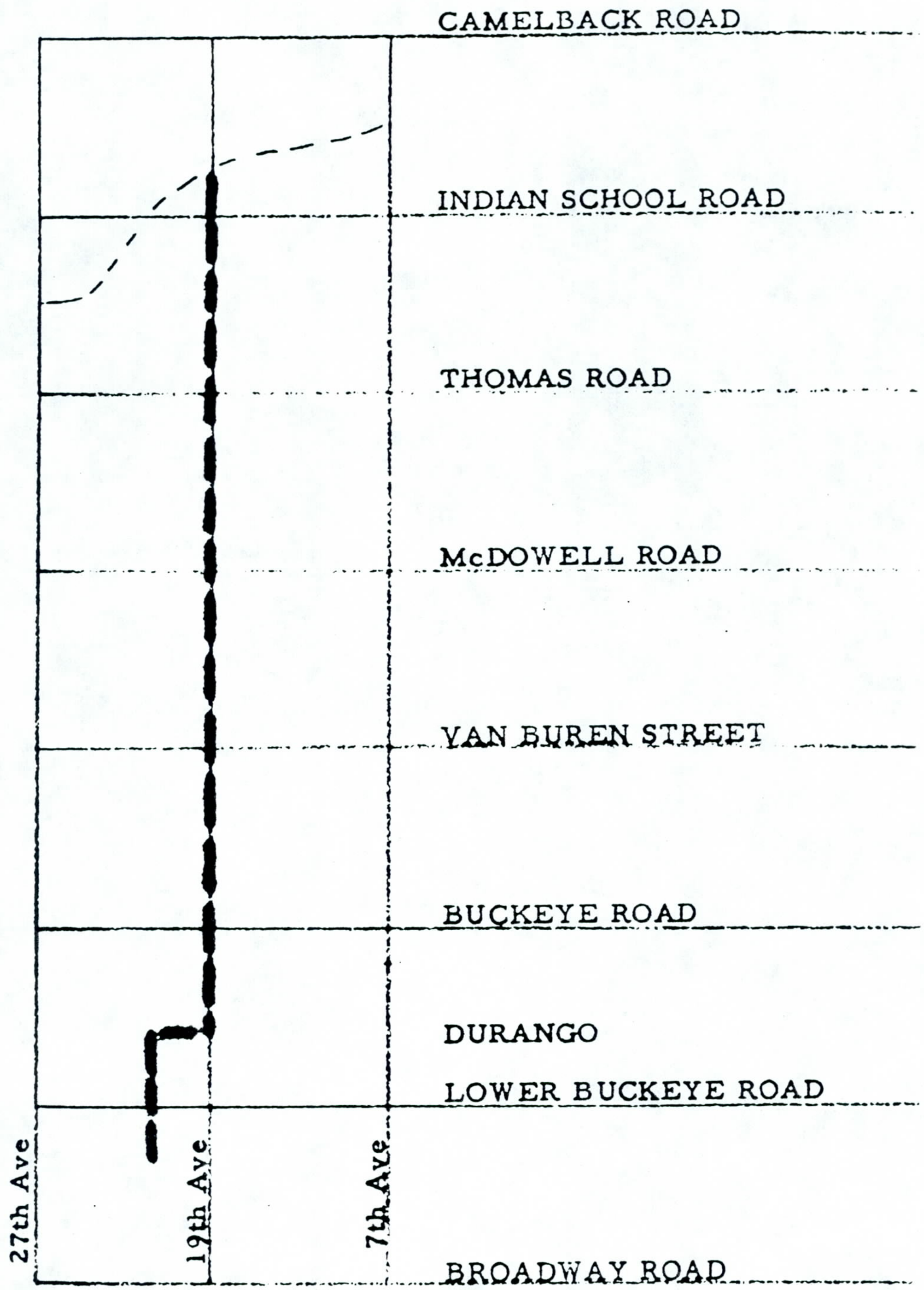
The soil resistivity test results and the graphs for the five foot, ten foot, and fifteen foot depths are reproduced herein as Plates 12, 13, 14, 15, 16, and 17.

Buck concluded as follows:

"A pipeline with these characteristics

1. 2 oz. galvanized coating
2. 10-14 gage wall thickness
3. a dipped asphalt coating

is not recommended for this installation as a storm sewer on 19th Avenue."

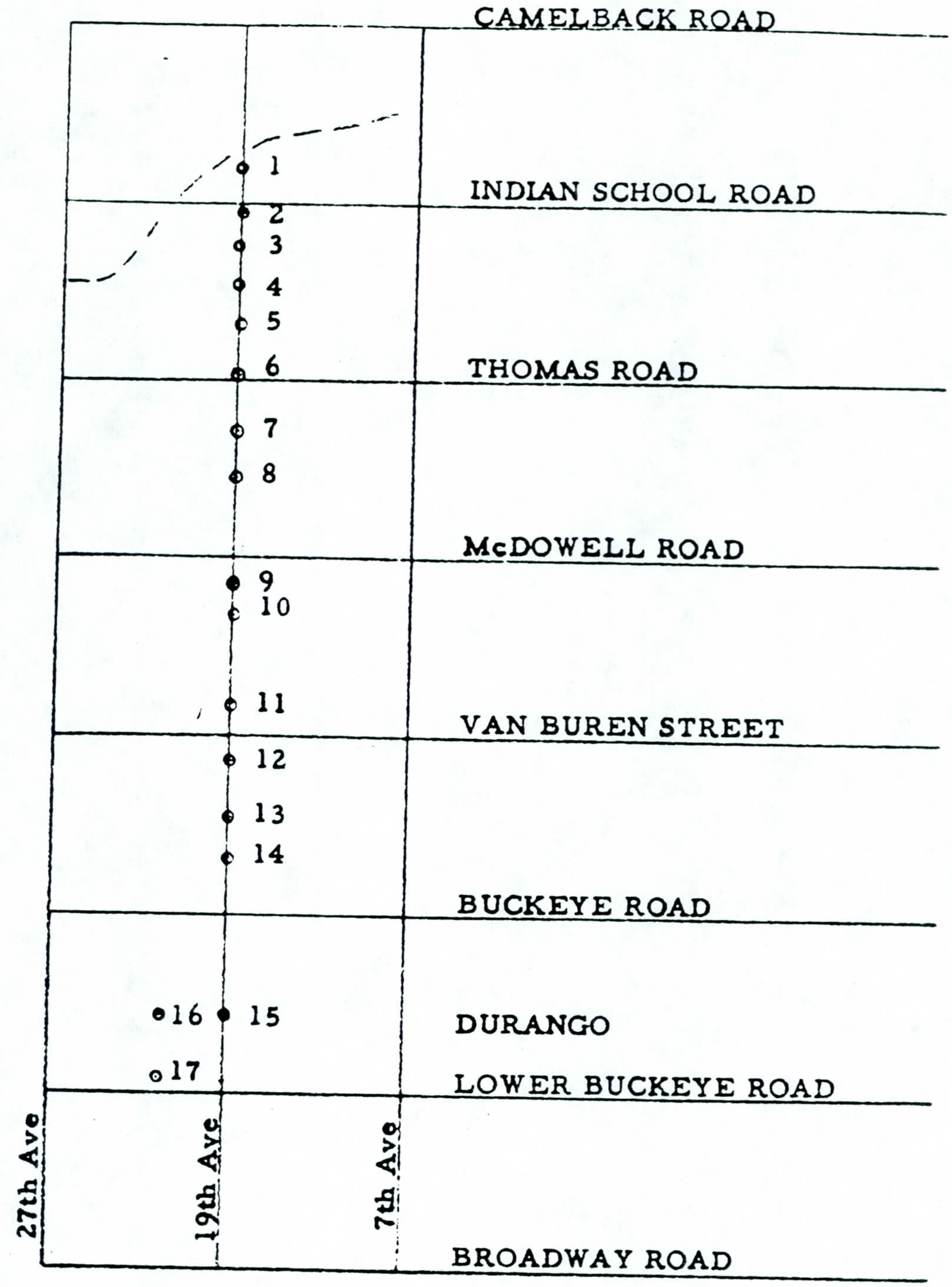


STORM DRAIN ROUTE

PLATE 12

PHOENIX, ARIZONA

1" = 1 MILE



SOIL RESISTIVITY TEST SITES

STORM DRAIN ROUTE

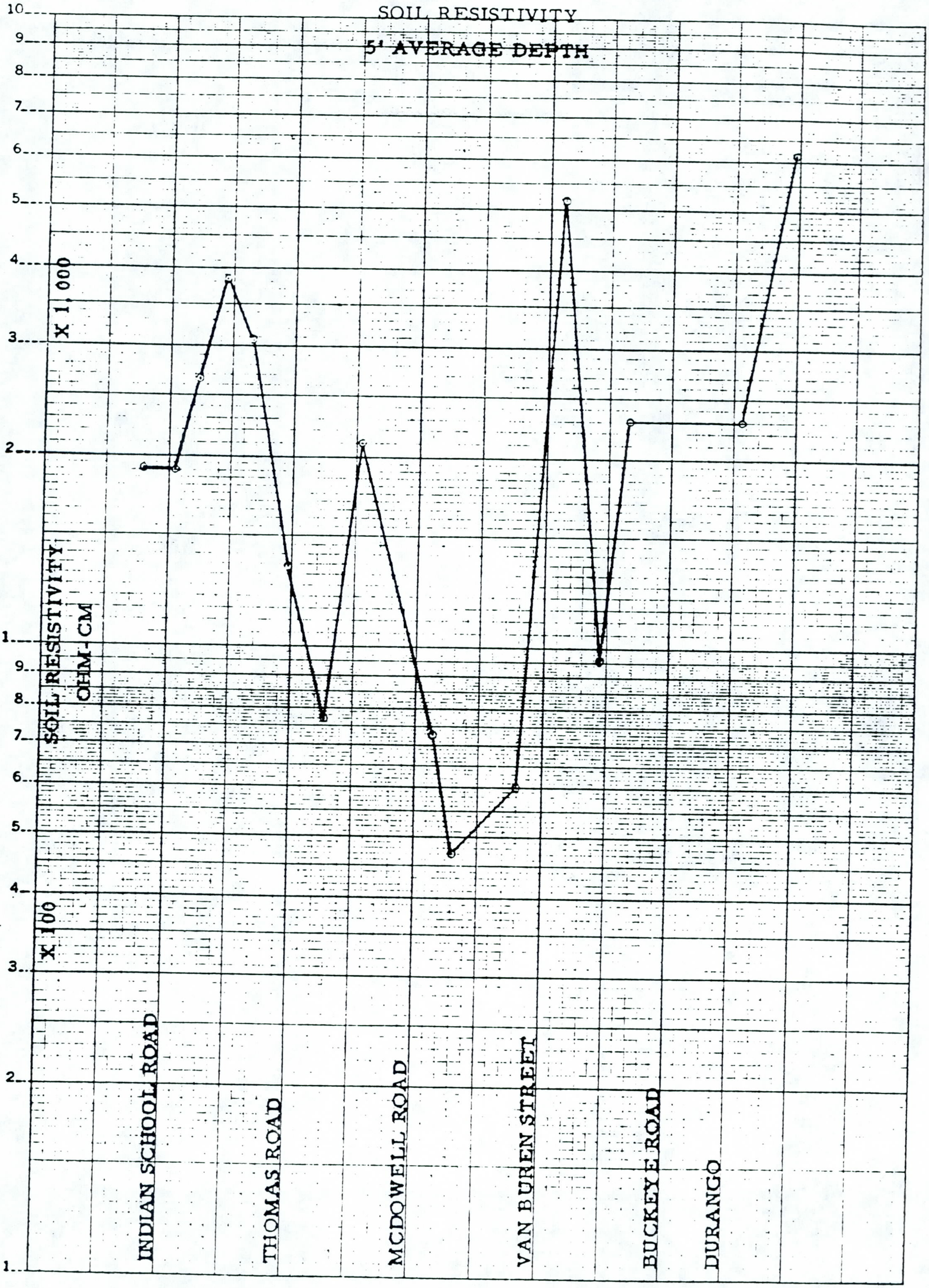
PHOENIX, ARIZONA PLATE 13 1" = 1 MILE

PLATE 14

STORM SEWER ROUTE

SOIL RESISTIVITY TESTS

STATION NUMBER	LOCATION	AVERAGE DEPTH	RESISTIVITY OHM-CM
.80	SW Corner - Grand Canal and 19th Avenue	5	1910
		10	2300
		15	1440
1.05	NE Corner - Amelia and 19th Avenue	5	1910
		10	2870
		15	2870
1.23	SW Corner - Indianola and 19th Avenue	5	2680
		10	2300
		15	1720
1.45	SE Corner Mitchell and 19th Avenue	5	3830
		10	2680
		15	1780
1.68	NW Corner 19th Avenue and Flower	5	3060
		10	2300
		15	1900
1.98	NE Corner 19th Avenue and Thomas Road	5	1340
		10	1720
		15	1440
2.28	NE Corner 19th Avenue and Virginia	5	770
		10	1150
		15	1150
2.52	SE Corner 19th Avenue and Encanto	5	2110
		10	1920
		15	2010
3.14	NW Corner 19th Avenue and Willetta	5	730
		10	1920
		15	1840
3.30	SE Corner 19th Avenue and Spruce	5	480
		10	610
		15	1260
3.80	SE Corner 19th Avenue and Fillmore	5	650
		10	1150
		15	1210
4.12	SW Corner 19th Avenue and Monroe	5	5170
		10	3830
		15	1340
4.44	NW Corner 19th Avenue and Jackson	5	960
		10	1300
		15	1320
4.68	SE Corner 19th Avenue and Lincoln	5	2300
		10	3830
		15	8620
5.56	500' S of Durango on 19th Ave	5	2300
		10	2680
		15	3450
5.92	200' S of Durango on 22nd Ave	5	6130
		10	4020
		15	7470
6.32	22nd Ave & Salt River Lower Buckeye Road	5	95,700
		10	84,200

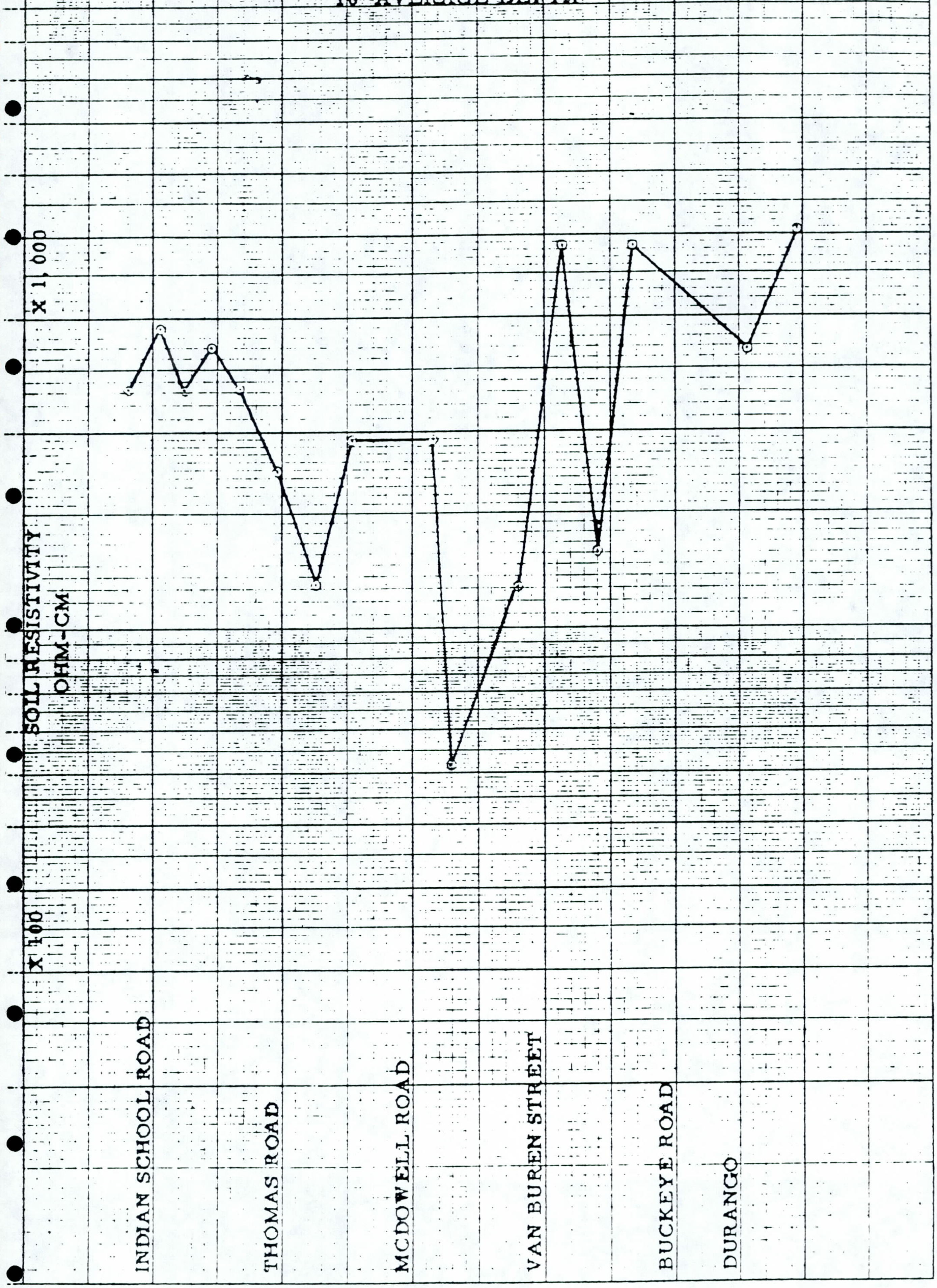


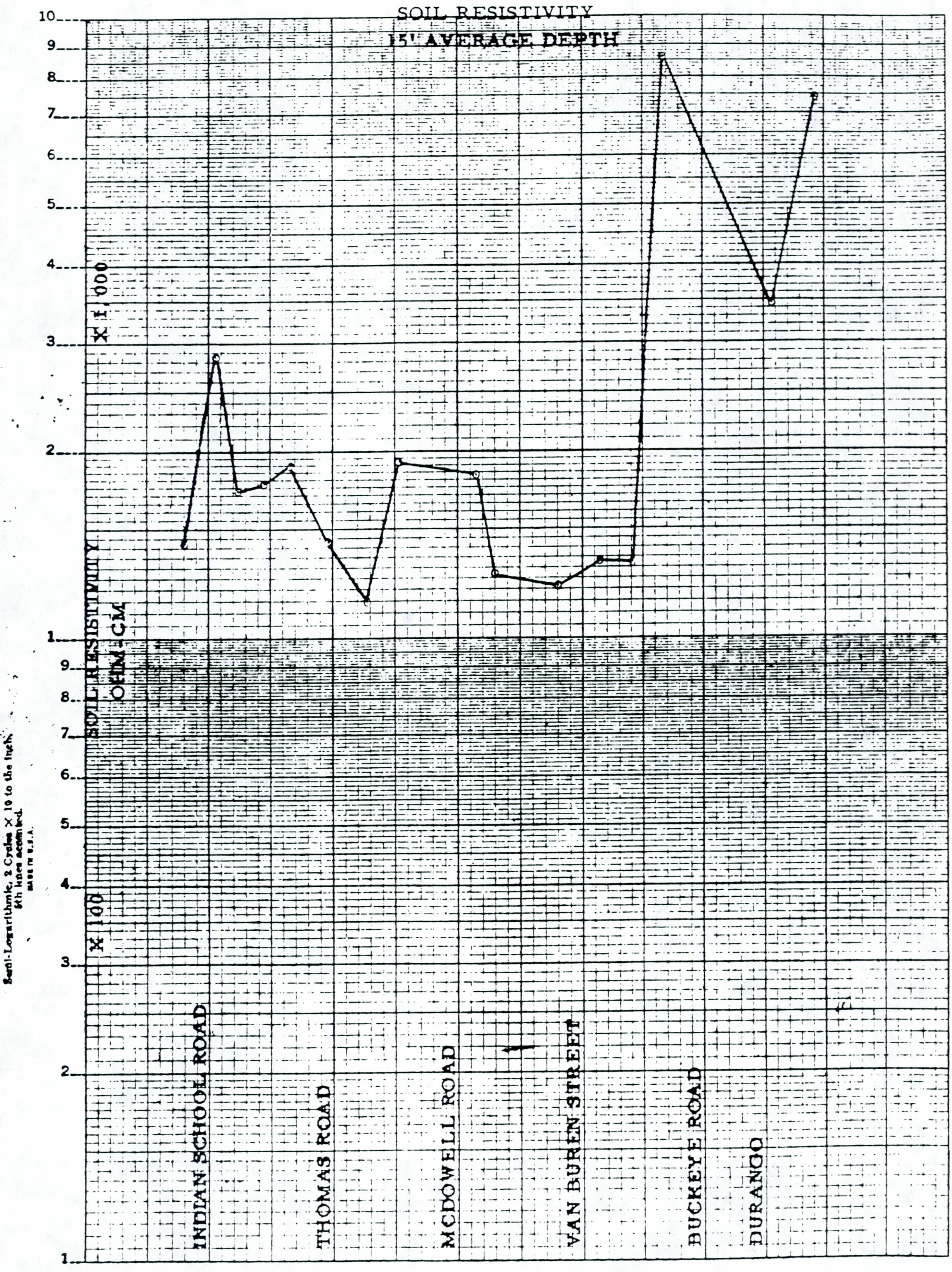
SOIL RESISTIVITY
5' AVERAGE DEPTH
SOIL RESISTIVITY
OHM-CM
X 1,000
X 100
INDIAN SCHOOL ROAD
THOMAS ROAD
MCDOWELL ROAD
VAN BUREN STREET
BUCKEYE ROAD
DURANGO

PLATE 15

SOIL RESISTIVITY

10' AVERAGE DEPTH





SOIL RESISTIVITY
15' AVERAGE DEPTH
SOIL RESISTIVITY
OHM-CM
X 1,000
X 100
10
9
8
7
6
5
4
3
2
1
INDIAN SCHOOL ROAD
THOMAS ROAD
MCDOWELL ROAD
VAN BUREN STREET
BUCKEYE ROAD
DURANGO
KEUFFEL & ESSER CO.
Semi-Logarithmic, 2 Cycles X 10 to the inch

NOTES:

1. City of San Diego, "Drainage Design Manual", April 1984 (Ref. 28). This manual was received too late to provide a detailed review. It provides an excellent presentation of "Basic Policies" plus detailed design criteria.

2. References 29 through 38 consist of published technical bulletins and handbooks issued by various pipe manufacturers or associations. These publications provide valuable technical information, however, it was not considered necessary to include abstracts of them in this literature review.

EVALUATION AND CONCLUSIONS

A. INTRODUCTION

This evaluation is based upon a review of literature consisting of: 1) reports by various state departments of transportation; 2) reports by federal agencies; 3) reports by city and county agencies; and publications by national institutes (e.g. ACI, AISI) and manufacturers. These references are listed at the end of this evaluation report.

Most of the reports reviewed were based upon investigations of corrugated metal culverts. Very few addressed reinforced concrete pipe or storm drain piping. While many of the results of the culvert investigations can be judiciously applied to storm drain installations, it must be kept in mind that there are differences in both interior and exterior environment which must be considered in this evaluation. Three types of pipe storm drains are evaluated herein, namely: 1) reinforced concrete pipe; 2) cast-in-place concrete pipe (non-reinforced); and 3) corrugated steel pipe. Most evaluations in the literature compare storm drain piping systems using four basic parameters. These are: 1) Structural Adequacy; 2) Hydraulic Capacity; 3) Durability; and 4) Economics.

B. STRUCTURAL ADEQUACY

1. Reinforced Concrete Pipe

This pipe (RCP) is generally specified to be manufactured in accordance with ASTM C-76. This is a "detail" type spec, in which the wall thickness, and compressive strength of the concrete, and the area of circumferential steel reinforcement are prescribed for each diameter and class of pipe (e.g. D-Load) specified by the purchase. In cross section, the pipe is designed as a self-contained, or rigid section not dependent upon the passive lateral soil pressure of the pipe trench walls. Trench bottom should be shaped to "cradle" the pipe, and the haunches and sides of the bedding should be given adequate compaction (e.g. 90%) to one foot over the top of the pipe to minimize settlement or misalignment of the pipe, or possible settlement of the trench surface. The city of Phoenix Supplement to MAG Specifications[32] contains sections on bedding (601.4.2) and backfill (601.4.3) which are suitable for reinforced concrete pipe installation. ASTM C-76 provides a design factor of safety of 1-1/2:1, being the ratio of the D-load to produce the ultimate load to the D-load to produce a 0.01-inch crack.

2. Cast-in-Place Concrete Pipe

   a. Lynch Manual Approach (Information taken from LYNCH MANUAL[31])

      i. General

         Cast-in-place concrete pipe (CIPP) is a non-reinforced concrete pipe formed, placed, and compacted against a rounded undisturbed trench bottom and vertical undisturbed trench walls. The concrete is placed and held in position by a self-propelled piece of equipment and supporting interior temporary metal plates. The rounded trench bottom provides excellent bottom support for the pipe, and the direct contact of the sides of the pipe with the undisturbed soil of the side walls provides lateral support for the pipe. Lateral support is required for the pipe because it is not designed as a self-contained rigid structure.

ii. Vertical Earth Loads

The Lynch Manual describes the theory of vertical earth loads on conduits as developed by Marston and Spangler at the Iowa Engineering Experiment Station.

The Lynch design tables are developed from the Marston and Spangler theories. A family of curves is presented (Dwg. 7, pg 67 of the manual) for determining earth load coefficients as a function of the ratio of "H" to "B" (H = depth of cover, B = width of trench). (See Plate 18)

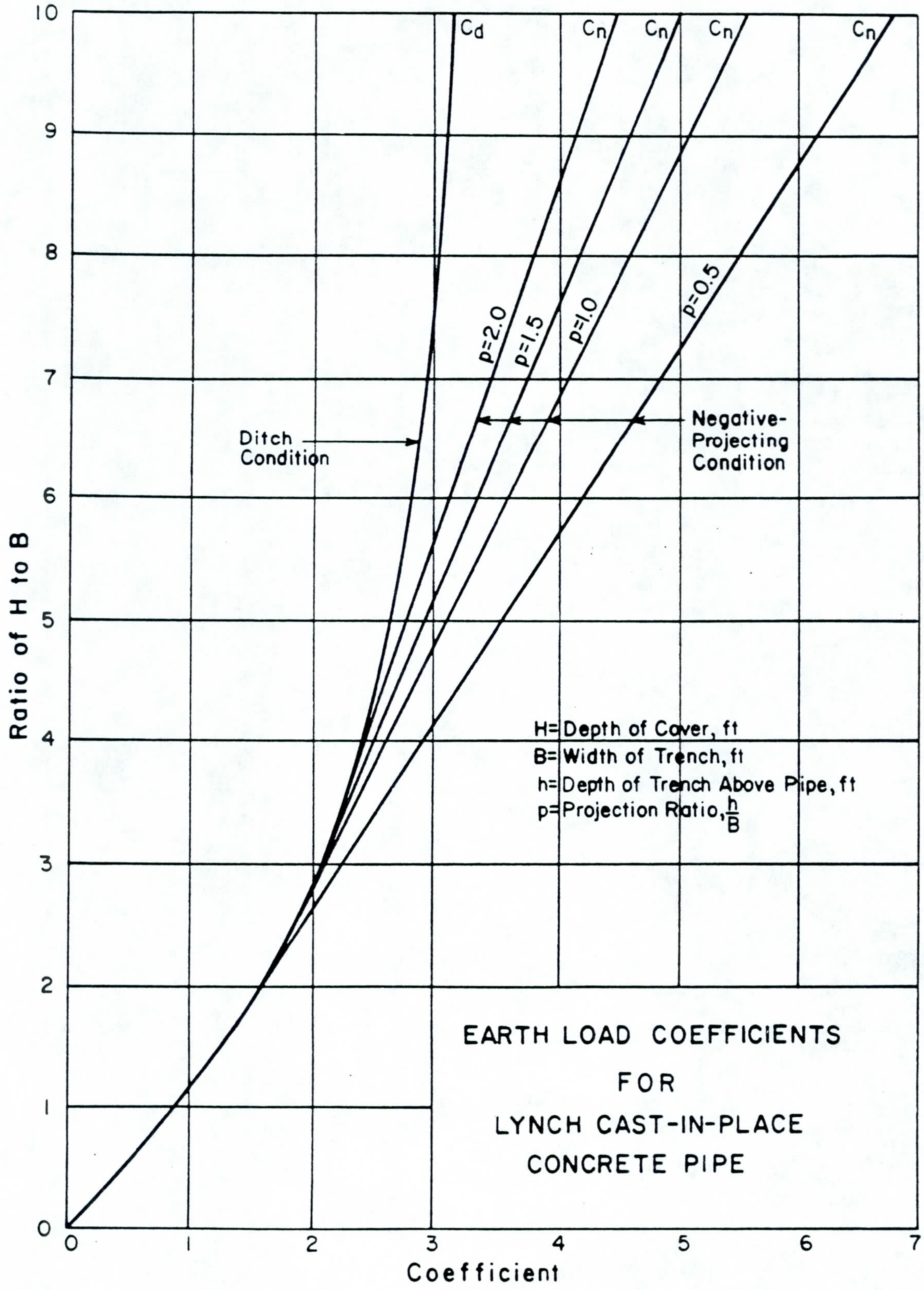
iii. Other Stress Producing Factors

The manual also describes in detail other stress producing factors, including 1) wheel loads; 2) the weight of the pipe; 3) the water within the pipe; 4) a possible head of water above the pipe; and 5) the lateral thrust of the soil against the sides of the pipe.

iv. Lateral Soil Thrusts

Regarding item 5, lateral soil thrusts the manual states as follows:

> "An extremely important loading factor in the strength considerations of a buried conduit is that of the lateral force exerted against the pipe by the active thrust of the soil mass. This force is commonly computed as the average depth below the surface, multiplied by the unit weight of the soil adjacent to



Cd
Cn
Cn
Cn
Cn
p=2.0
p=1.5
p=1.0
p=0.5
Ditch Condition
Negative-Projecting Condition
H= Depth of Cover, ft
B= Width of Trench, ft
h= Depth of Trench Above Pipe, ft
p= Projection Ratio, h/B
EARTH LOAD COEFFICIENTS
FOR
LYNCH CAST-IN-PLACE
CONCRETE PIPE
Ratio of H to B
Coefficient
0
1
2
3
4
5
6
7
8
9
10

DRAWING 7

the trench, and multiplied by a factor commonly referred to as the "hydrostatic ratio" or the "Rankine Factor". This value in turn is multiplied by the outside depth of the pipe to obtain the load per lineal foot."

"The Rankine factor depends upon the properties of the soil and its method of placement, and its value varies greatly in the judgement of soils engineers. This lateral load is obviously a much greater value and consequently much more important with greater depths of the pipe. It is particularly critical when the pipe is placed in the negative-projecting condition under a high embankment."

v. Design Approach

In Chapter V of the manual the design approach is explained as follows:

"Introduction

The structure-soil interaction between Lynch CIP concrete pipe and the surrounding soil is complex, different from that of precast conduits, and subject to only approximate analysis. A frequently used approach has been to apply elastic-arch theory for determination of thrust and moment at critical sections. A number of assumptions must necessarily be used."

"An early (November 10, 1921) presentation in

Engineering News-Record by James Paris[12] has been applied by such later writers as Womack and Kirdar[20] of the Salt River Project in Phoenix, Arizona, and Ernest Fortier[3], a consulting engineer in Fresno, California. Loading cases examined by Paris which are particularly applicable to cast-in-place concrete pipe are (1) uniformly distributed loading on top of the pipe and the resulting uniform support, (2) uniform and wedge-shaped horizontal soil loading, (3) the effects of the weight of the pipe and of the water within the pipe."

"It can be seen by inspection that the most critical stress situation will commonly occur in a section of the invert of the pipe. Consequently, attention can be focused at that location. Table X on page 82 (see Plate 19) presents coefficients for thrust and moment at the pipe invert for the several types of loading mentioned above. These coefficients have been adapted from the work of the writers previously mentioned."

"The problem of design then becomes one of determining maximum net combinations of thrusts and of moments for conditions of loading in a particular situation. Such net moments thrusts can be translated into stresses, which in turn can be compared with the strength characteristics of the concrete."

Considering thrust and movement from lateral loads, the

Lynch Manual, on page 75 states as follows:

"Thrust and Moments from Lateral Loads

Computation of stresses in Lynch CIP concrete pipe must include the effect of lateral soil pressure against the pipe. Because the pipe is poured against the undisturbed, in-place, natural soil which acts as the side form, intimate contact is maintained between the pipe and the soil beside it. Consequently, the soil is a positive force against the pipe."

"Soil mechanics theory (Ref. 16) explains the lateral (horizontal) pressure in a soil which results from the weight of the overlying earth whereas the vertical stress is a function of the unit weight of the soil multiplied by the depth of the overburden, the determination of the lateral stress is more complex."

"In more simplified presentations, the lateral pressure is often expressed as a proportion of the vertical pressure, (often called the Rankine Ratio). The ratio in a given soil depends upon the internal characteristics of the soil mass -- friction, cohesion, structure, grain size and shape, and grain-size distribution. The most commonly used value of this ratio is one-third. That figure will be used in the standard computations herein."

Table X previously referred to is reproduced herein as Plate 19. It should be noted in Table X that the thrusts

TABLE X

EQUATIONS FOR THRUST AND MOMENT AT INVERT OF LYNCH CIP CONCRETE PIPE FROM APPLICABLE LOADINGS AND REACTIONS

LOADING	HORIZONTAL THRUST AT INVERT, lb	MOMENT AT INVERT, ft-lb
Uniform Distributed Load Top and Bottom	$T_v = 0$	$M_v = +.125VR$
Uniform Lateral Load	$T_{L_u} = +1.000z_uR$	$M_{L_u} = -.250z_uR^2$
Triangular Lateral Load	$T_{L_t} = +1.375z_tR^2$	$M_{L_t} = -.292z_tR^3$
Weight of Water in Pipe	$T_W = -.451\ W_w$	$M_W = +.070\ W_WR$
Head of Water Above Pipe	$T_{h_1} = -31.2\ h_1D$	$M_{h_1} = 0$
Weight of Pipe	$T_P = +0.027W_p$	$M_P = +.070RW_p$

M = Moment, ft-lb/lin ft

T = Thrust, lb/lin ft

R = Radius to center of shell (average radius), ft

V = Vertical (earth & live) load on pipe, lb/lin ft

W_W = Weight of water in pipe, lb/lin foot = $62.4\ \frac{\pi}{4} D^2$

W_P = Weight of pipe, lb/lin ft.

z_u = Average unit lateral pressure (uniform loading), lb/sq ft = kHw'

z_t = Unit lateral soil pressure (triangular load), lb/sq ft = Kw'

h_1 = Head of water above soffit, ft

w' = Density of soil beside trench, lb/cu ft

k = Rankine ratio

D = Internal diameter of pipe, ft

D' = Outer depth of pipe, ft

and moments for the lateral loads are of opposite sign than the other principal loads, which means that the summation of thrusts and moments are reduced by the lateral loads. It would appear that no adjustment is included for variations in the soil density of the undisturbed soil. The Rankine Ratio (here assumed as 1/3) is based upon average densities under embankment conditions.

For cast-in-place concrete pipe calculations some adjustment should be made in either "k", the Rankine Ratio, or Z_u and Z_t, through a lowering of the value of w; the density of the soil adjacent to the trench, in situations where the soil density is less than 90%.

vi. Factory of Safety

The critical stress, according to the manual, is the net tensile stress (tensile flexural stress plus thrust stress) in the concrete. This net tensile stress is compared to the flexural strength (modulus of rupture) to determine what factor of safety is provided. The manual contends that a factor of safety of 2, used by some engineers, is too high, and suggests instead a ratio of 1:1 1/3. The manual reads as follows:

> "The fatigue limit of concrete, established at 50 to 55 percent of the modulus of rupture, is based upon an infinite number of stress reversals; this does not occur in buried pipe. The earth load is steady; repetitions of axle loads are neither infinite in

number nor reversals of stress. Concrete continues to acquire strength with aging and also has some capacity to creep and, therefore, will tend to remain in lateral contact with the soil under vertical load. Load failures have historically not occurred in CIP concrete pipe and commonly would not be catastrophic if they did occur."

b. Criteria Regarding Spanlger/Marston Formulae.

i. Bureau of Public Roads

Two reports by the Bureau of Public Roads[18,19] deal with the structural design criteria and recommended installation practice for corrugated metal pipe. The discussions concerning bedding, side fill and compaction are applicable not only to corrugated metal pipe but to other types of buried flexible pipe as well.

ii. The 1966 Bureau Report

The 1966 report states in Section 2.1 as follows:

> "Values of E^1 (passive soil pressure), and "k" soil stiffness coefficient used in Criterion II are interdependent and are influenced by the quality of the side fill material and the degree of compaction (density) thereof. The design charts have been prepared on the basis of normal installation conditions, which require a value of 700 psi for E^1 with good side fill material compacted to 85 percent Proctor Density which is estimated to have a soil

stiffness coefficient k = 0.44. The use of better quality side fill material with a greater degree of compaction will increase the value of E^1. Correspondingly the value of k will decrease in numerical value which means conversely a higher value of ultimate buckling stress f_b. With excellent side fill material (graded gravel or crushed stone) compacted to 95 percent Proctor Density it is estimated that a value of E^1 = 1400 psi (and value of k = 0.22) may be used for special designs. Special designs shall be used only when the engineer is reasonably certain that requirements for excellent side fill material with 95 percent compaction can be met.

iii. The 1970 Bureau Report

The 1970 report states in Section 2.2 as follows:

"2.2 Criterion II - Critical Buckling of Pipe Wall. This criterion provides for the design of pipe based on the wall area required for a limiting buckling stress which takes into account the restraining effect of the soil structure around the pipe. The restraining effect of the soil structure (side fill material) depends on the characteristics of the side fill material and its density (degree of compaction) and is reflected in the value of the soil stiffness coefficient, k, which ranges from 1.0, representing no restraint, to 0.00 which represents an ideal condition of full restrain. ... where the quality of side fill material and compaction required for k = 0.22 are not obtainable, buckling should be investigated for a value of k = 0.44 and E^1 = 700 psi."

iv. Summary

In the section on installation, the 1966 report, on Figure 3, page 13, and the 1970 report, on Figure 1, page 12 indicate that the side fill for embankment shall extend outward for a minimum of 2 D minimum, up to 12 feet maximum. Note "c" on Figure 1 of the 1970 report states as follows:

"Side fill to be compacted in 6-inch layers to density specified for adjacent embankment but not less than 95% Proctor Density."

On page 13 of the 1970 report, the final paragraph reads as follows:

"It is again emphasized that these design charts and tables are predicted on obtaining, in the field, the quality of side fill material and compaction that are specified in Section 3, Installation, and upon the use of the above basic data, where the degree of inspection and quality and compaction of side fill material obtainable on the site are such as to make it doubtful whether the above installation requirements can be met, fill heights should be calculated from design charts based on values of E^1 = 700 and k = 0.44."

Neither report addresses finite value requirements for existing soil. Since CIPP is cast-in-place against the existing undisturbed soil, the soil should have similar values of E^1 and k to those required of embackment, e.g. the undisturbed soil should have a minimum Proctor Density of 95% in order to use values of E^1 = 1400 and k - 0.22."

v. U. S. Bureau of Reclamation

The U. S. Bureau of Reclamation in 1977 analyzed available data from over 100 projects which included various pipe materials, pipe diameters, backfill depths, and installation conditions, and published back-calculated values of E^1 which were related to the pipe bedding material and the degree of compaction. The recommended values of E^1 range from 50 to 3,000, and were verfied by laboratory tests. The enclosed Table 4 (Plate 20) indicates the bureau's findings and are presented here to indicate the wide variation in soil reaction and the magnitude of the variation of soil reaction based upon the degree of compaction, (% Proctor Density).

vi. Analogy to Ring Stress Design Theory.

The Lynch design method utilizes the Spangler approach to determine vertical earth loads on the pipe, but does not use the Spangler approach for determining lateral earth load, but instead uses the Rankine Ratio approach.

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/in^2)			
	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/ft^3 (ASTM D-698, AASHTO T-99, USBR Designation E-11).

U.S. Bureau of Reclamation
January, 1977

Regardless of which approach is selected the precautions and limitations mentioned in the two Bureau reports are still applicable.

c. Conclusions

It is concluded that cast-in-place concrete pipe can be structurally designed to function as a storm drain, with certain restrictions as follows:

i. The undisturbed soil adjacent to the proposed storm drain trench should be sampled at frequent intervals to determine % Proctor Density and % relative density, and the allowable design stresses be determined by these values.

ii. A minimum factor of safety of 2.0 should be used in determining allowable design stresses.

iii. Cast-in-place concrete pipe should not be installed in locations where a minimum of two pipe diameters (up to 12' maximum) of the storm drain cannot be maintained between the storm drain and other existing or proposed utilities, or designated utility corridors, except that the above clearances may be reduced to one storm drain pipe diameter (up to 6' maximum) in cases where the other utility is or will be installed not less than 6 vertical feet above the top of the storm drain.

iv. Cast-in-place concrete pipe should not be installed in soft, spongy, or expansive material, or in ground incapable of standing vertically unsupported from the bottom of the trench to the height equivalent to the top of the pipe to be placed.

v. Prior to installation of cast-in-place concrete, the contractor should (by spec.) be required to submit detailed design data used in determining minimum pipe wall thicknesses required for the project under contract, clearly indicating all steps used in the calculations, including factors of safety. Installation of CIPP should not begin until the above submittal has been reviewed and approved by the city engineer.

3. Corrugated Steel Pipe

a. Structural Design

The Handbook of Steel Drainage and Highway Construction Products, 3rd Edition[29] in Chapter 3, Section B presents a description of the structural design of buried metal pipe using the ring compression theory. The allowable wall stress derivation incorporates a factor of safety of 2.0, and is modified by a load factor k based on the standard density of the soil adjacent to the trench.

In utilizing the figures and charts in this section for structural design, the specified Proctor Density of the bedding and backfill should be not less than 90%. The density to be used for pipe design should be based on the Proctor density of the undisturbed soil adjacent to the trench but not higher than 85%.

b. Bedding and Backfill

i. Bureau of Public Roads Recommendations

The two reports by the Bureau of Public Roads[18,19] stressed the importance of obtaining a uniform high (95%) Proctor Density in the bedding material for pipe dependent upon lateral pipe/soil interaction, suggesting that the bedding material from the invert to one foot over the pipe should be placed and compacted in 6-inch layers to 95% Proctor Density by either hand or mechanical tmapers. The reports also suggested that the 95% density should extend two pipe diameters -- up to 12 feet maximum on either side of the pipe. It was also stated that "Ponding or jetting of side fill is not generally recommended."

ii. City of Phoenix Specifications

The City of Phoenix supplement to MAG specifications[32] treats bedding as follows:

> "601.4.2 Bedding: Bedding shall be Selected Material Type B or Aggregate Base as per Table 702. Open graded rock will not be used without the written approval of the engineer."
>
> "Where water consolidation is used, bedding for conduits, 24 inches or less in I.D., may be placed in one lift. For larger conduits, the first lift shall not exceed the springline of the pipe."
>
> "Where mechanical compaction is used, the moisture content shall be within a range of +2 to -4% of the

optimum moisture content prior to placing the material in the trench. The first lift shall be eight inches or 2/3 of the distance to the springline whichever is greater. Succeeding lifts shall not exceed one foot loose and extreme care will be taken to prevent damage to or movement of the conduit by the compaction."

iii. Conclusion

- The method of bedding compaction presented in the Bureau of Public Roads reports, using hand or pneumatic tampers, while appropriate for normal culvert installations, may not be appropriate for most storm drain installations under "trench" conditions because of safety considerations. All safety rules should be complied with, including OSHA. Therefore when safety rules preclude the use of hand or pneumatic tampers for bedding compaction, some other method must be used which (for flexible pipe such as CSP) will provide a suitable Proctor Density.
- The present city specification does not fulfill the need for not less than 90% Proctor Density (95% preferred) in a uniform manner. It should be noted that the placing and compaction of backfill in the city specification is tighter than the requirements for bedding. The Phoenix specification obviously favors water consolidation over mechanical compaction, a viewpoint which is opposite to the 1966 and 1970

recommendations of the Bureau of Public Roads.

- Bedding compaction methods (for CSP) should be evaluated by a competent soils engineer to determine the best method of obtaining the desired Proctor Density in a uniform manner. Other methods have been suggested, one of which involves the use of select material enhanced with a lean mix ratio of, say, one sack of cement per cubic yard of mix. Another alternate involves the use of new or reject seal chips, vibrated into place in layers.

c. Structural Design Submittals

Prior to delivery of CSP to the site of the work the contractor should (by spec.) be required to submit detailed design data used in determining pipe shell thickness required for the project under contract, clearly indicating all steps used in the calculations, including factors of safety. Pipe should not be accepted at the site of the work until the above submittal has been received and approved by the city engineer.

C. HYDRAULIC CAPACITY

1. General

Hydraulic capacity of a pipe is usually determined by Manning's formula which is:

$$V = \frac{1.486}{n} R^{2/3} S^{1/2}$$

and, since Q = AV

$$Q = A \frac{1.486}{n} R^{2/3} S^{1/2}$$

in which

Q = flow, cubic feet/second
A = cross-sectional area of pipe flow in square feet
R = Hydraulic radius in feet = area divided by wetted perimeter
S = slope, or grade in feet/feet
n = coefficient of roughness of pipe interior (dimensionless)

The cross-sectional area of the pipe, A, the hydraulic radius, R, and the pipe slope, S, can be calculated for any given set of conditions. However, the coefficient of roughness, n, is a matter requiring judgement. Many studies and experiments have been conducted on various types and sizes of pipes. These are usually conducted on straight sections of pipe, clean, using clear water. Judgement must be used in applying the coefficient to expected field conditions, taking into account bends in the line, joints, and possible inclusion of debris in the pipe line.

2. Reinforced Concrete Pipe

Reinforced concrete pipe manufactured in accordance with ASTM C-76 has a relatively smooth interior surface, but occasionally has scattered blemishes where the surface has been repaired with grout. RCP equipped with rubber gasket joints is sometimes installed without filling the interior joints with grout to provide continuity of the interior surface. Grout is required in joints of RCP with tongue and groove joints. Loss of grout in either case can cause a very slight increase in the roughness coefficient, n. Although some tests indicate that a coefficient of n = Ø.Ø11 could be used for RCP, Ø.Ø12 - Ø.Ø14 is a more conservative range for storm drain design. This should be reviewed after field inspections have been made, which will investigate debris build up and abrasion of the concrete surface.

3. Cast-in-Place Concrete Pipe

Specifications for Cast-in-Place Non-Reinforced Concrete Pipe are contained in Bulletin ACl 346-81 by the American Concrete Institute. Recommendations are contained in Bulletin ACl 346R-81. In Section 3.2.2 of the latter bulletin, the coefficient of friction is discussed. Based upon a series of 281 tests by the Salt River Project in 1966, in cooperation with the Bureau of Reclamation, it was found that 241 of the tests, or 86 percent had values of 0.013 or less. Only 26 tests, 9 percent gave values higher than 0.014, the recommended n factor. Bulletin 346R-81 also suggested that a value of 0.015 or higher perhaps should be used, based upon field investigations of pipe surface and debris accumulation.

4. Corrugated Steel Pipe

a. Values for "n", Helical vs. Annular Corrugations

i. Discussion

Coefficients of roughness for CSP vary according to the surface treatment of the pipe interior. Tests have been undertaken on values of n for helically corrugated steel pipe and the results are presented in "Handbook of Steel Drainage and Highway Construction Products" by the American Iron and Steel Institute[29], 1983. It states on page 186 as follows:

"Tests on helically corrugated pipe demonstrate a lower coefficient of roughness than for annularly corrugated steel pipe when there is a significant amount of helix or spiral in the pipe. For a given diameter, the greater the (angle of) helix, the less the friction factor. For a given helix, the greater the diameter, the less the friction factor."

"Values for 5 x 1 inch corrugations are based on tests made on 6 x 1 inch corrugations modified for the shorter pitch. Most published values of the coefficient of roughness, n, are based on experimental work under controlled laboratory conditions, using clear or clean water. The lines are ordinarily straight and with smooth joints. However, design values should take into account the actual construction and service conditions which vary greatly for different drainage materials."

Table 4-9, (Plate 21) page 185 of the AISI Handbook provides values of coefficient of roughness, n, for various diameters of helical pipe, for all diameters of annular corrugated pipe, for three corrugation patterns, and for three conditions of interior pipe surface (unpaved, 25% paved, and fully paved). For example, unpaved pipe with 2 2/3 x 1/2 inch annular corrugations gives a value of n of Ø.Ø24 for all diameters, while for helical corrugations the value of n varies from Ø.Ø12 for 8-inch pipe to Ø.Ø18 for 36-inch pipe to Ø.Ø21 for 6Ø-inch and larger. Based on the limited tests and straight pipe conditions described on

Friction Loss, (H_f) is the energy required to overcome the roughness of culvert barrel and is expressed in the following equation:

$$H_f = \frac{(29\ n^2L)}{(R^{1.33})}\ \frac{V^2}{2g} \ldots\ldots\ldots\ldots (12)$$

ere: n = Manning's friction factor, See Tables 4-10 and 4-11
L = length of culvert barrel, ft
V = mean velocity of flow in barrel, ft/sec
g = acceleration of gravity, 32.2, ft/sec²
R = hydraulic radius, or $\frac{A}{WP}$ (ft)

stituting in equation (10) and simplifying (for Bernoulli's Theorem) we for *full flow:*

$$H = \left(1 + k_e + \frac{29\ n^2L}{R^{1.33}} \right) \frac{V^2}{2g} \ldots\ldots\ldots\ldots (13)$$

Fig. 4-20). Nomographs for solving equation (13) are shown in Reference 10.

gure 4-25 Balanced culvert design assures practical minimum end areas.

Table 4-9 Values of Coefficient of Roughness (n) for Standard Corrugated Steel Pipe (Manning's Formula)*

Corrugations	Annular 2⅔ × ½ in. All Diameters	Helical 1½ × ¼ in. (11, 12) 8 in.	Helical 1½ × ¼ in. (11, 12) 10 in.	Helical 2⅔ × ½ in. 12 in.	Helical 2⅔ × ½ in. 18 in.	Helical 2⅔ × ½ in. 24 in.	Helical 2⅔ × ½ in. 36 in.	Helical 2⅔ × ½ in. 48 in.	Helical 2⅔ × ½ in. 60 in. and Larger
Unpaved	0.024	0.012	0.014	0.011	0.013	0.015	0.018	0.020	0.021
25% Paved	0.021					0.014	0.017	0.020	0.019
Fully Paved	0.012					0.012	0.012	0.012	0.012

Corrugations	Annular 3 × 1 in.	Helical—3 × 1 in. 48 in.	54 in.	60 in.	66 in.	72 in.	78 in. and Larger
Unpaved	0.027	0.023	0.023	0.024	0.025	0.026	0.027
25% Paved	0.023	0.020	0.020	0.021	0.022	0.022	0.023
Fully Paved	0.012	0.012	0.012	0.012	0.012	0.012	0.012

Corrugations	Annular 5 × 1 in.	Helical—5 × 1 in. 54 in.	60 in.	66 in.	72 in. and Larger
Unpaved	0.025	0.022	0.023	0.024	0.025
25% Paved	0.022	0.019	0.020	0.021	0.022
Fully Paved	0.012	0.012	0.012	0.012	0.012

*AISI

page 186 of the handbook (see quote above) they are of a lower value of n for helical pipe than for annular corrugated pipe does not appear to be justified.

ii. Conclusion

It is concluded that a value of n of Ø.Ø24 should be used for corrugated steel pipe with 2 2/3 x 1/2 inch corrugations, and a value of n of Ø.Ø27 for corrugated steel pipe with 3 x 1 inch corrugations.

b. Protective Coatings and Paving

Based upon our review of the literature a suitable lining or paving has yet to be found whch can consistently demonstrate a satisfactory service life of 5Ø years. Reports concerning asphalt lining and paving were very inconsistent, many linings failing in less than ten years, while a few other locations indicated service up to 27 years. Asphalt, being extremely flammable, is not recommended for use in storm drains. Concrete lining is being used, however its longevity has not been established for this purpose. Several instances have been reported where the concrete has lost its bond with the steel in a relatively short period of time. Thus if the lining/paving is not expected to last for the design service life of the pipe, the value of "n" in the Manning formula must be based upon the corrugated surface of the steel rather than on the concrete surface.

D. DURABILITY

1. Background

a. AISI Handbook

Durability is defined in the 1983 AISI Handbook (Ref. 29, page 231) as follows:

> "Durability is defined as the ability of the culvert to function properly for its design life." The paragraph continues: "The culvert must exhibit continued structural soundness during this time. It is of little value for the culvert material to endure if structural distress impairs performance. Durability must include all types of deterioration, not merely material attrition. It is proper to include in the design for durability, such things as disjointing, cracking, and settlement as well as erosion, corrosion, and abrasion.

The AISI Handbook also states, under the heading INVESTIGATIONS as follows:

> "Virtually every state has now made some investigation into culvert durability. This has resulted in field observations and laboratory tests on a total of more than 43,000 culverts. This mass of work has made it possible to evaluate culvert durability for specific areas or environments. With the durability guess work statistically removed, the engineer may now specify the proper corrugated steel pipe culvert to assure satisfactory performance for the particular environment and flow.

b. Federal Highway Administration TA 5040.12

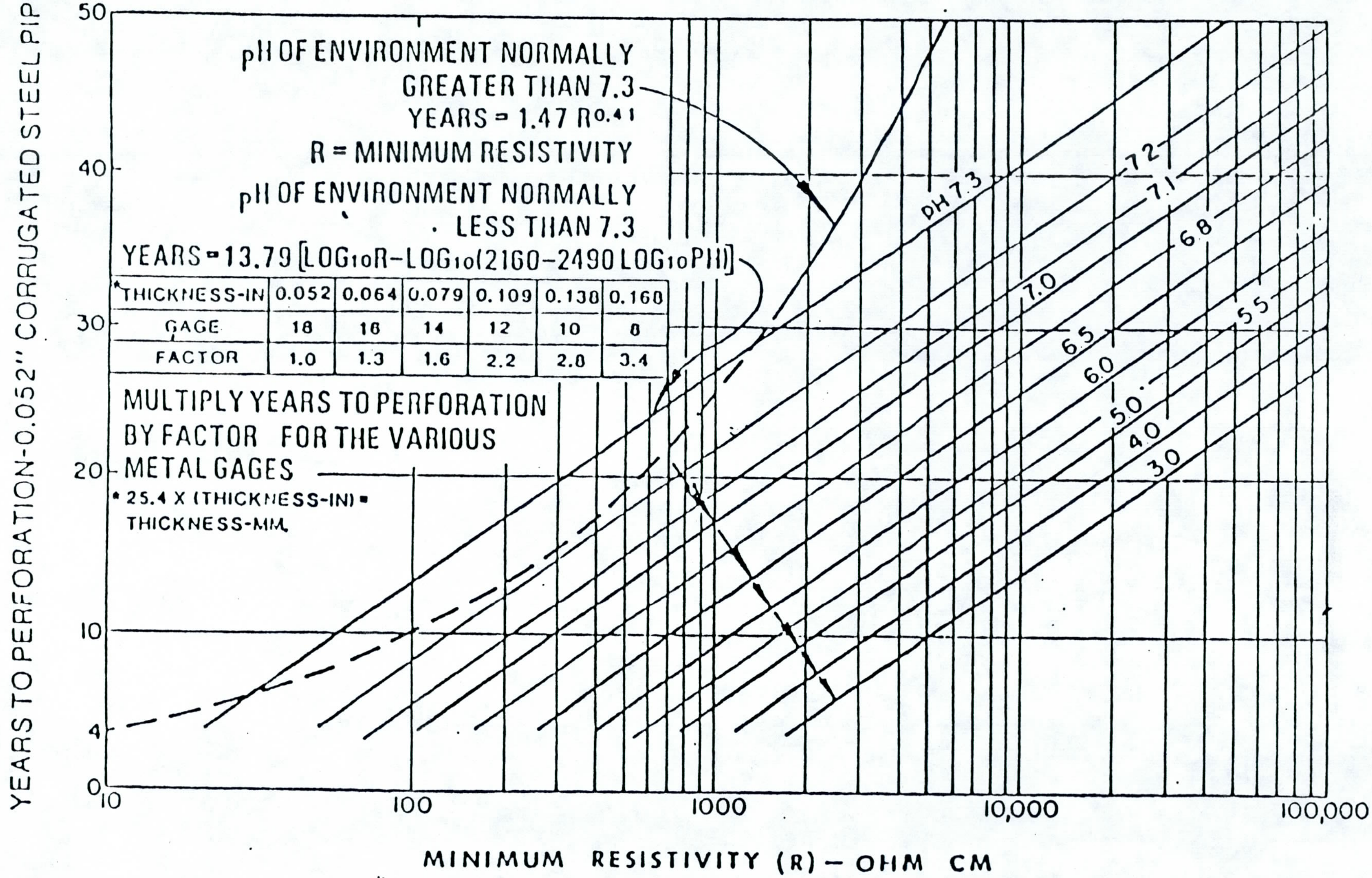
FHWA Technical Advisory TA 5040.12[20] in Section 5 GUIDELINES, states as follows:

i. "General. The following guidance is offered relative to designing for durability and for help in determining the suitability of galvanized steel and aluminum alloy corrugated metal pipe. It is pointed out that any reference to specific service life in terms of years is absent, primarily because drainage structure design engineers have been unable to agree on a definition of pipe failures and on what service life should be provided. Some engineers design on the basis of time to first perforation; others calculate time to reduce the structural safety factor to one. Regardless of the method used to determine estimated service life, it should be recognized that the result is still an estimate and not an absolute value."

The statement in the FHWA Technical Advisory is, on the basis of my review of the literature, more accurate than the statement presented in the AISI Handbook.

c. Divergence of Views By Individual States

The findings of the highway departments of California[2], New York [11], Ohio[13] and Utah[17], when compared, indicate the divergence of viewpoints. California developed a chart for estimating metal culvert corrosion rate in 1962. The chart was replaced by Figure 7-351.3 dated April 2, 1979 in their Highway Design Manual (Plate 22). It is repeated here for purpose of



REFERENCE: TEST METHOD NO. CALIF. 643

CHART FOR ESTIMATING YEARS TO PERFORATION OF CORRUGATED STEEL PIPE

PLATE 22

comparison). New York, on a probabilistic basis, in 1984, determined that the state could be divided into two zones. Based on their field studies Zone I was assigned a metal loss rate for design of 2 mils/year, and Zone II was assigned a metal loss rate of 4 mils/year. They also established an end point to service life for design purposes -- defined as the point when the culvert invert or flow line would be completely removed as if the design metal loss rate occurred uniformly throughout the length of the culvert. Ohio conducted an in depth field investigation and subsequently developed charts indicating "'years to poor'" for concrete pipe and corrugated steel pipe. The charts, their figures No. 30 and No. 31 (Plate 23 and 24) in their 1982 report are repeated here for comparison purposes. Utah published a report in 1974 in which two charts where presented, their Figures 23 and 24 (Plate 25 and 26). The charts, entitled "Material Selection Criteria" include total soluble salts as a criterion in addition to pH and minimum resistivity.

d. Service Life End Points

The Ohio report, in our judgement, provides an excellent chart for predicting the service life for concrete pipe, expressed as 'years to poor'. Their concrete rating classification for 'poor' includes the following visual features: A. Significant loss of mortar and aggregate; B. Complete loss of invert; C. Concrete in softened condition. For Phoenix we would suggest adding a fourth condition for reinforced concrete, as D.

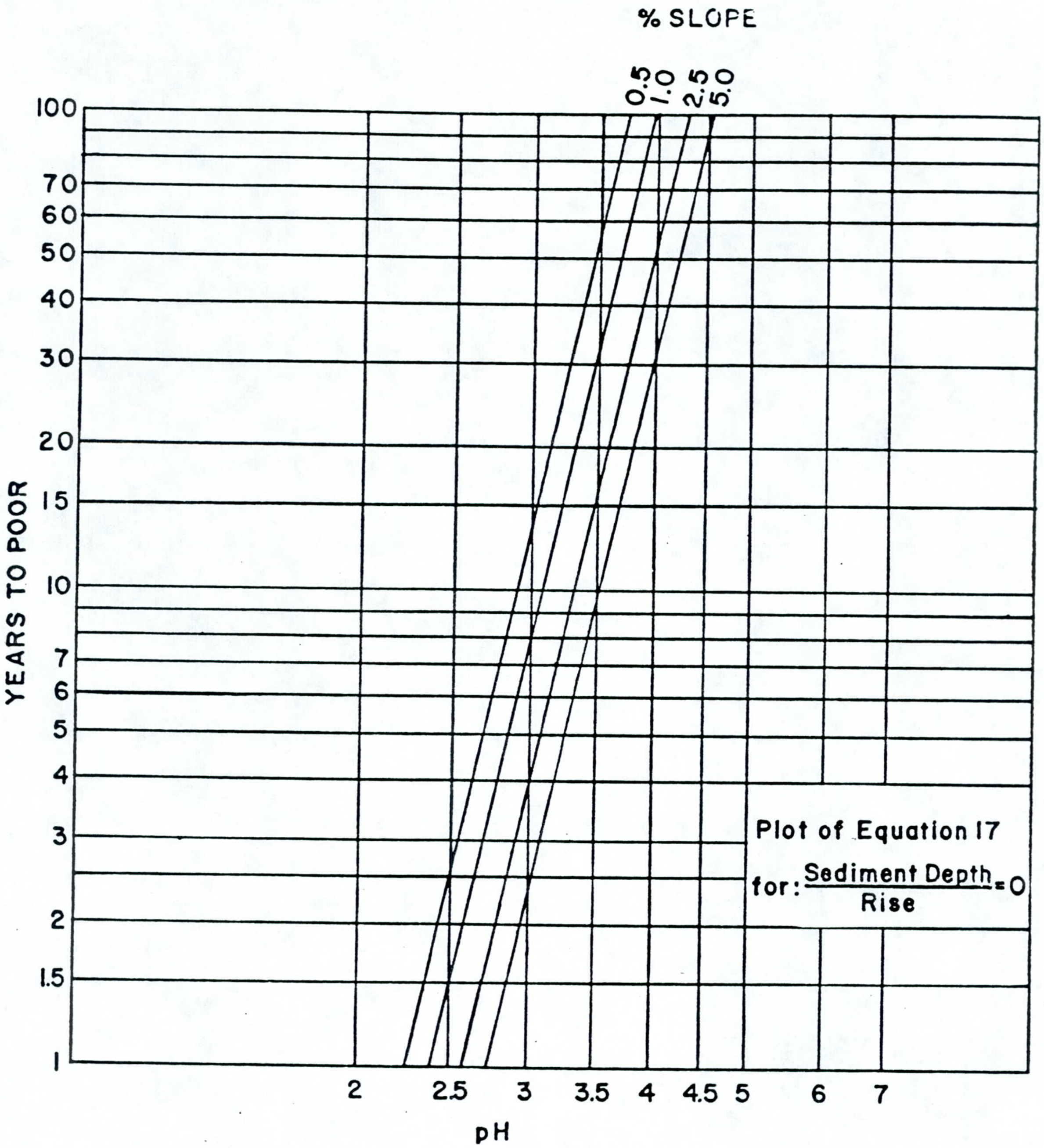


Figure 30. Plot of Predictive Equation 17 for concrete pipe culvert life.

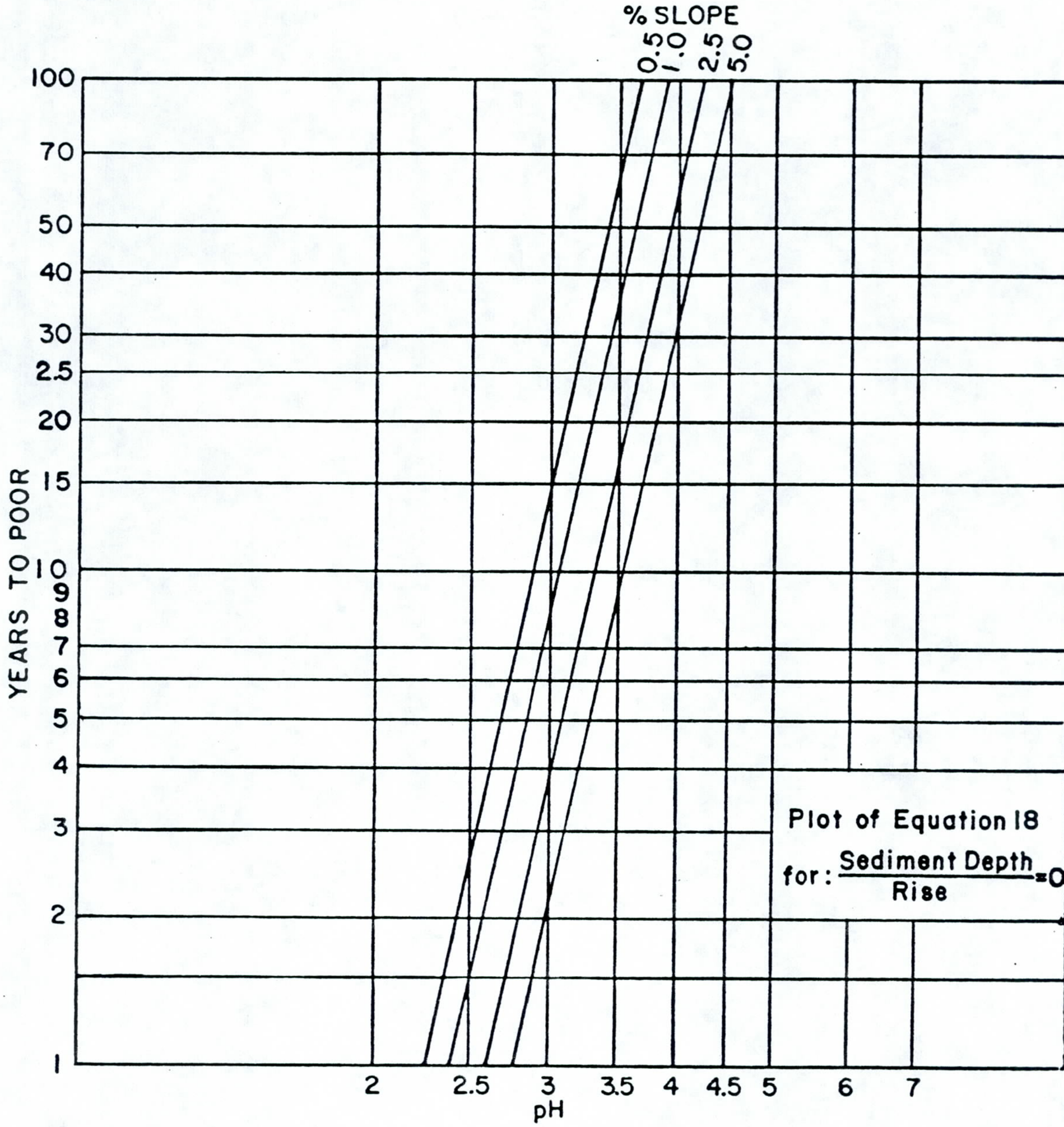
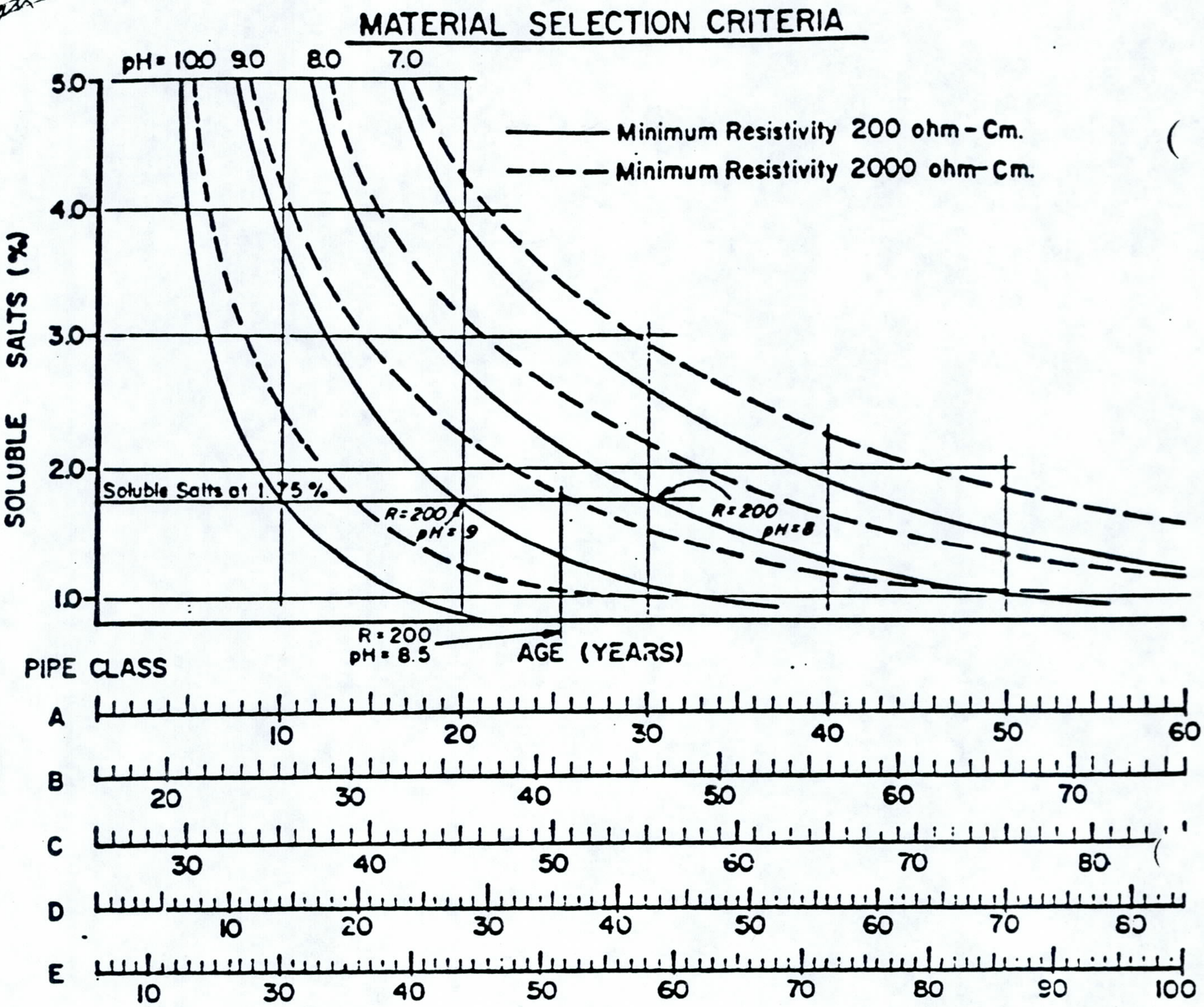


Figure 31. Plot of Predictive Equation 18 for concrete pipe culvert life.

Utah Report



Pipe Class A = Plain corrugated steel pipe.

Pipe Class B = Bituminous Coated Corrugated Steel Pipe, Aluminum Alloy Pipe, Galvalume Pipe, Pitch-Resin adhesive coated corrugated Steel Pipe (coated on outside only).

Pipe Class C = Asbestos Bonded Bituminous Coated Corrugated Steel Pipe, Pitch-Resin adhesive Coated Corrugated Steel Pipe (coated on Both sides).

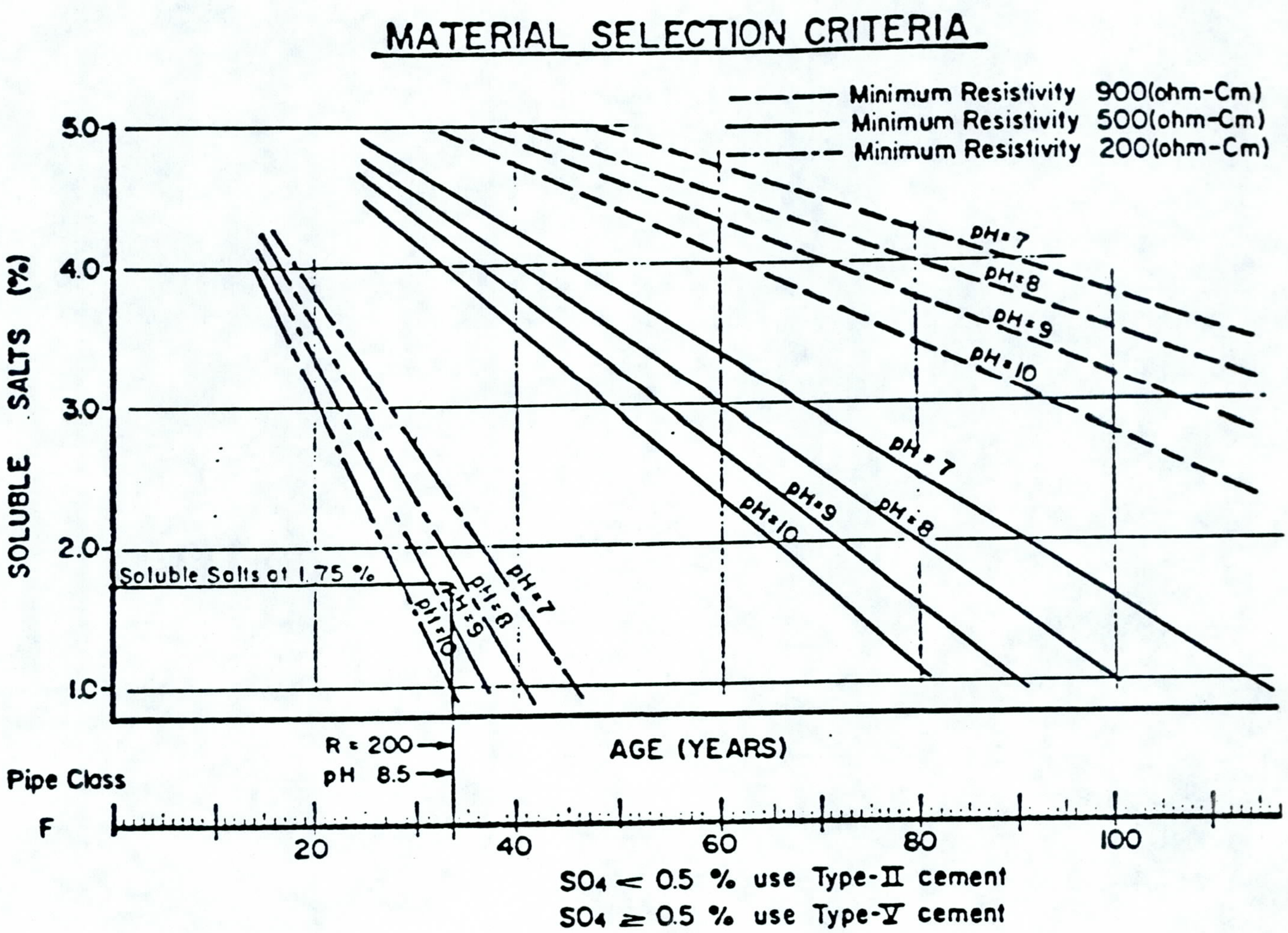
Pipe Class D = Plain Corrugated Steel Structural Plate Pipe.

Pipe Class E = Bituminous Coated Corrugated Steel Structural Plate Pipe, Aluminum Alloy Structural Plate Pipe.

NOTE: All Steel Pipes are Galvanized.

Figure 23

Utah Report



Pipe Class F = Portland Cement Concrete Pipe
Type-II Cement ($SO_4 < 0.5$ percent)
Type-V Cement ($SO_4 \geq 0.5$ percent)

Figure 24

Exposure of steel reinforcing with significant metal loss. This condition alone is enough to signifiy an end to the pipe's service life. Conditions A, B, and C would apply also to cast-in-place concrete pipe.

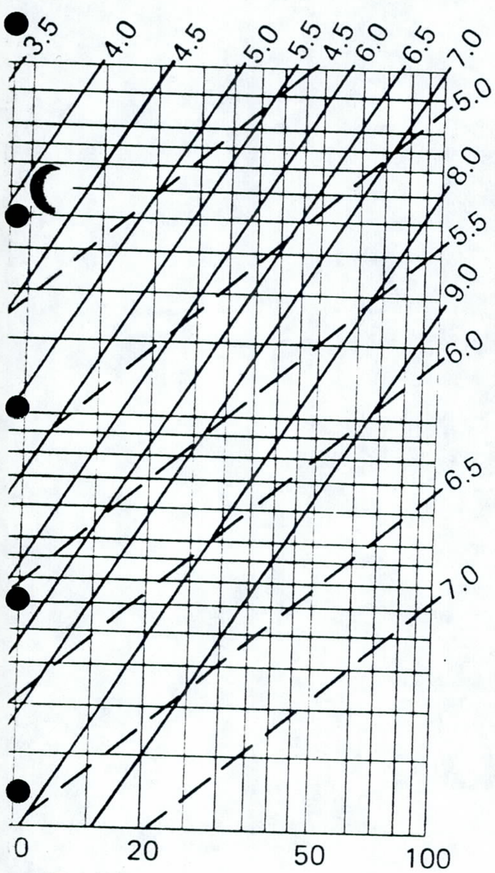
The Ohio report also provides a chart for predicting metal loss for corrugated metal pipe culverts. Tables III and IV (Plate 27) in ACPA Buried Facts No. 2, 1982[34] indicate the number of years to complete metal loss for a range of pipe gage thicknesses and a range of pH values. Complete metal loss would correspond to a metal rating classification of "Poor" in the Ohio report, characterized by the following conditions: A. Penetration with Geologist's hammer; B. Perforation; and C. Loss of invert. Under condition B-Perforation should be interpreted to mean first perforation.

An alternate chart for estimating service life of plain galvanized steel culverts is presented as Figure 5-4 (Plate 28) in the AISI Handbook,[29] page 238. However, it is important to note that the average life-years as determined from this chart should be divided by two. The chart was originally based upon a relationship between first perforation and average metal loss developed by Stratfull, Richard F., Chapter 7 "Durability", Modern Sewer Design, 1st Ed. AISI, 1980. The present Handbook rationalizes that the "years to perforation data" presented in reference 2 (our Ref. 2) should be increased by a 2 to 1 ratio. We disagree and conclude that the years to perforation should be based upon 1/2 the values presented in Figure 5-4.

CORRUGATED STEEL PIPE METAL LOSS

Figures 3 and *4* present metal loss in thousandths of an inch on the vertical scale and age in years on the horizontal scale. The solid diagonal lines represent pH of the water for use when there is a potential for abrasive flow and the dashed diagonal lines represent pH of the water for use when there is no potential for abrasive flow.

The predictive metal loss graphs are based on laboratory metal loss analysis of coupons obtained from 38% of the CSP culverts and 20% of the structural steel plate culverts which were included in the investigation and had exposed metal. Culverts with the inverts completely corroded away were not included in the analysis unless the time of failure could be estimated. Of the 613 CSP culverts, with and without protective coatings, which were included in the random sampling investigation, over 53% were observed to have experienced corrosion anywhere from pitting to complete loss of invert. For the plain galvanized CSP, this corrosion percentage increased to 76% with one third rated as being in *poor* condition.



YEARS

$3300\ (AGE)^{1.6042}\ (pH)^{-5.4446}$

$995{,}000\ (AGE)^{0.8427}\ (pH)^{-8.0583}$

oss for Structural Culverts.

Table III. Years to Complete Metal Loss With Abrasion.

Gage Thickness Ins.	pH 3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
16(0.064)	1.5	2.3	3.5	5.0	7.0	9.3	12	16	20	24	29
14(0.079)	1.7	2.7	4.1	5.8	8.0	11	14	18	23	28	34
12(0.109)	2.1	3.4	5.1	7.3	10	13	18	22	28	35	42
10(0.138)	2.5	3.9	5.9	8.6	12	16	21	26	33	41	50
8(0.168)	2.8	4.5	6.8	9.8	13	18	24	30	38	47	57
7(0.188)	3.0	4.9	7.4	11	15	20	26	33	41	56	62
5(0.218)	3.4	5.4	8.1	12	16	22	28	36	45	56	68
3(0.249)	3.7	5.9	8.9	13	18	24	31	40	50	61	75
1(0.280)	4.0	6.4	9.7	14	19	26	34	43	54	66	81

Table IV. Years to Complete Metal Loss Without Abrasion.

Gage Thickness Ins.	pH 3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
16(0.064)	1.5	2.3	3.5	5.6	8.8	13	19	27	37	49	64
14(0.079)	1.7	2.7	4.2	6.9	11	16	23	33	45	60	79
12(0.109)	2.1	3.4	5.8	9.5	15	22	32	45	62	83	100+
10(0.138)	2.5	4.1	7.3	12	19	28	41	57	78	100+	100+
8(0.168)	2.8	5.0	8.8	15	23	34	49	69	94	100+	100+
7(0.188)	3.0	5.6	9.8	16	25	38	55	77	100+	100+	100+
5(0.218)	3.4	6.5	11	19	29	44	64	89	100+	100+	100+
3(0.249)	3.8	7.4	13	21	33	50	72	100+	100+	100+	100+
1(0.280)	4.3	8.3	15	24	38	56	81	100+	100+	100+	100+

Rating	No.	Percent	
Poor	80	33.1	76%
Fair	41	16.9	
Good	63	26.0	
Very Good	46	19.0	
Excellent	12	5.0	
	242	100.0	

For any given metal thickness and pH value of the water, the number of years for the pipe invert to be completely corroded away can be readily determined by projecting a horizontal line from the given metal thickness on the vertical scale to the diagonal line representing pH and then projecting a vertical line down to the age in years on the horizontal scale. *Tables III* and *IV* were prepared from *Figure 3* and present years to complete metal loss for available corrugated steel pipe gage thicknesses and various pH levels. The tables illustrate that plain galvanized CSP has very limited service life over the full range of environmental conditions. When potential for abrasion is present, plain galvanized CSP should not be used and for the limited installations where potential for abrasion does not exist, plain galvanized CSP should only be considered under neutral environments with the heavier gage thicknesses.

Appropriate guidelines for the determination of whether or not abrasion was a factor contributing to the condition of the culvert were not established for the field investigation phase. However, the presence of abrasive material in the culvert at the time of the investigation was noted and the percentage of culverts with abrasive material present is presented in *Figure 5*. Of the culverts inspected, only four counties included culverts which did not have any abrasive material present at the time of the inspection. These

Figure 5-4
CHART FOR ESTIMATING AVERAGE LIFE OF PLAIN GALVANIZED CULVERTS

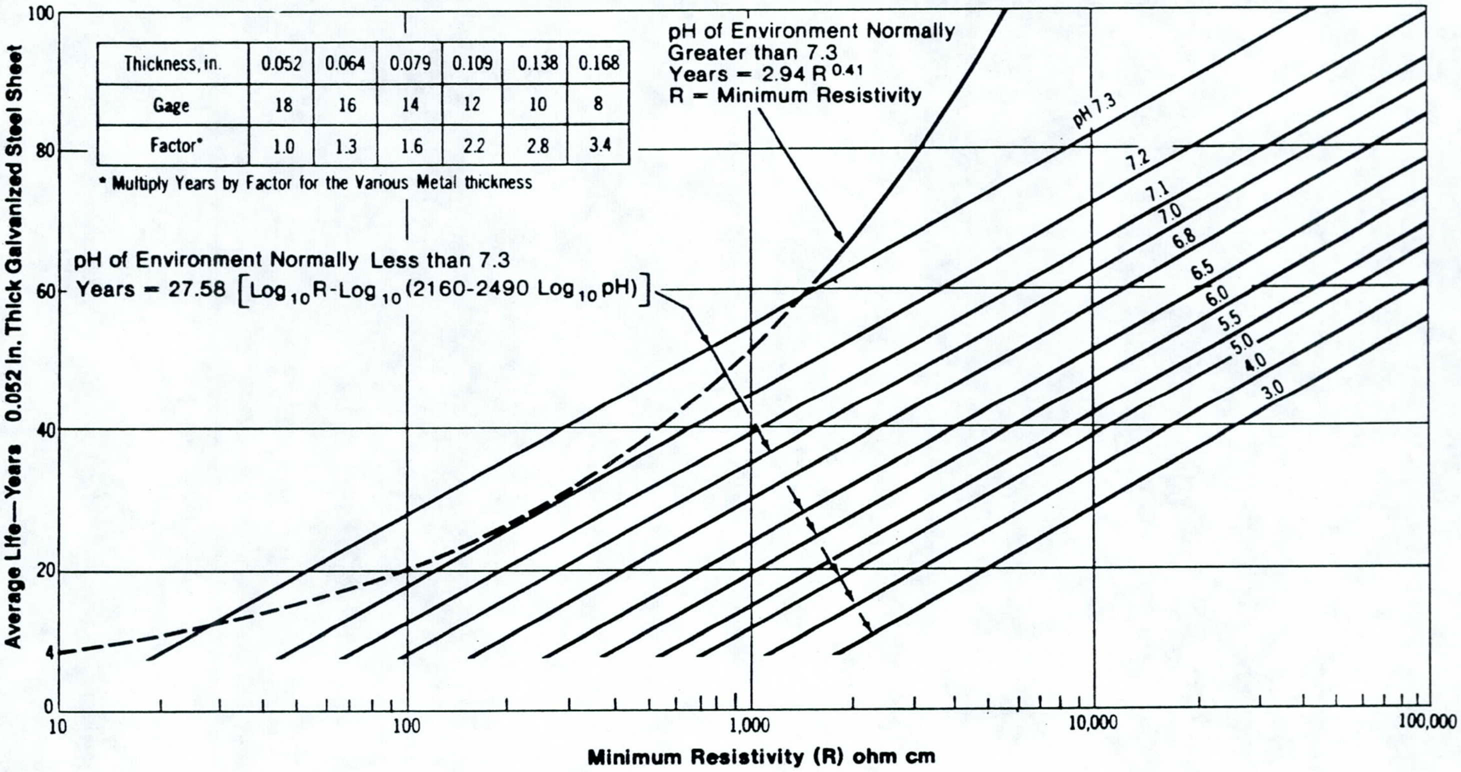


PLATE 28

Estimating Average Life

Using the minimum resistivity and pH values measured or estimated, ente the chart in Figure 5-4 to obtain the average life for 0.052 in. thick uncoate galvanized steel pipe. Convert this figure to the metal thickness desired b using the multipliers shown in the box in the upper left corner of Figure 5-4

For example, a measured resistivity of 3,000 ohm cm and a pH of 7 would result in an average life for 0.05 in. thickness of 48 years. If an actu thickness of 0.079 in. is required structurally, a multiplier of 1.6 is require Applying the 1.6 factor to 48 results in 76.8 years estimated average life fo 0.079 in. thick uncoated galvanized steel.

Other Metallic Coatings

In addition to the traditional zinc coated steel, aluminum coated and alu minum-zinc coated steel are available.

ABRASION

The affect of abrasion is included in the statistical data developed i California[2] and used herein for predicting average life. The California stud was based principally on culverts in an environment with pH values les than 7.3. They were located in high rainfall mountainous areas in whic significant abrasion could occur. The test method does not separate cor rosion from abrasion, but relates the total effect of both to time. Therefore when the geographic area involved is such that abrasion is not a factor, th use of Figure 5-4 may be somewhat conservative. Investigations in som states found this to be the case. Some have reported[17] that where few rock are present such as in Central United States, abrasion is not expected Investigations in such states as Florida, Georgia, Louisiana, Idaho, Ne braska and Kansas have indicated this to be true in those areas. Other have found that heavy loads of sand and small gravel size material ca cause significant abrasion. It is most important to rely on site experienc in making judgements on the effects of abrasion.

e. Protective Coatings

Credit may be given for protective coatings applied to corrugated steel pipe. Up front credit of a number of years corresponding to the estimated life of the protective coating to the point of metal exposure will extend the service life of the steel pipe by an equivalent amount. Several types of coatings such as aluminized steel pipe, and concrete are now being used on a trial basis and should be evaluated from time to time to determine the longevity of the coating. It is strongly suggested that flammable materials such as asphalt not be used as a lining or paving of the pipe interior.

f. Design Service Life

The service life of a storm sewer to be specified for any particular location should be based upon a policy established by the city of Phoenix, and upon any special conditions of a project as determined by the City Engineer. Consideration should be given not only to first cost and replacement cost, but also disruption of traffic, inconvenience to the public, disruption of other utilities, and obsolesence. Pipe culverts for state highway projects are commonly designed for a minimum service life of 50 years, and are in some cases designed for a service life of up to 100 years. As state highways are subject to relocation it is usually not advisable economically to design for longer periods. City streets, especially with a predominant grid pattern such as in Phoenix are not as susceptible as state highway routes to relocation. Consequently the minimum design service life for Phoenix storm drains should be 50 years. The three types of pipe, namely; reinforced concrete pipe, cast-in-place concrete pipe, and corrugated steel pipe can all meet the 50-year design requirement. Additionally, a minimum design service life of 100 years should be required as a matter of policy under any of the following conditions:

i. The pipe is to be located within a right-of-way of a major arterial street (existing or proposed) e.g. one-mile and half-mile grid streets, parkways, and others as determined by the City Engineer.

ii. The height of cover over the pipe is in excess of fifteen feet.

iii. The storm drain is to be located adjacent to or between structures which are horizontally a distance equal to or less than the depth of pipe cover from the structure to the center line of the pipe.

iv. The storm drain is to be designed to operate under a pressure head.

The design limitation of fifteen feet given in item 2 above and in the following discussion is admittedly an arbitrary selection. It should be recognized that the costs of installation and time of construction increase with increasing depth of trench. As a practical matter it is concluded that at some point of trench depth the inconvenience to the public and the disruption to traffic outweighs other considerations and the longer design service life should be required as a matter of policy.

g. Design Criteria

i. Depth of Cover

Storm drains should be limited to a maximum depth of cover of fifteen feet. However, depth of cover more than fifteen feet may be permitted in cases of necessity, that is, there being no viable alternative, but only with the approval of the City Engineer.

Storm drains which will have more than twenty five feet of cover should be designed with a service life of 100 years minimum, and they should be over-sized to permit the installation of a metal plate liner which will carry the design flow and retain full structural strength.

ii. Dead Load and Live Load

The unit earth load and minimum D-load should be stated for each type of pipe.

iii. Design Calculation Submittals

Prior to delivery or installation of any storm drain pipe the Contractor should be required to submit detailed design calculations for each diameter of pipe and for each variation in wall thickness.

h. Reinforced Concrete Pipe

RCP is considered to be suitable for a design service life of 100 years plus, with the following limitations. For anticipated water pH of 5.0 or less the storm drain should be either invert paved or fully lined with an acceptable liner. Flammable lining material should not be used. For soil pH of 5.0 or less the storm drain should be given protective coating. For high sulfate levels in soil or storm water Type V cement should be used in place of Type II.

i. Cast-in-Place Concrete Pipe

Cast-in-place concrete pipe has a potential under favorable conditions of having a service life of 100 years. This has yet to be demonstrated by 100 years of service. Some restrictions should be observed. Like RCP, the storm water and soil pH values should not be less than 5.0. Also the soil material in which the storm drain is to be constructed must be stable and unyielding when staurated, and non-expansive.

The design approach noted in the Lynch Manual[31] relies partially upon the theories developed by Spangler and Marston. The Bureau of Public Roads[18,19] in their reports cautioned the readers regarding the ideal conditions under which the authors developed their theories, such as a minimum Proctor Density of 95% in the sidewalls. This caution was presented herein in the Section Structural Adequacy. The design of cast-in-place concrete pipe should be based upon the lateral support to be provided by the undisturbed trench side walls in which the Proctor Density may be significantly lower than 95%. The design stresses used in the determination of wall thickness and other factors should be based upon the measured Proctor Densities to be encountered, and should in all cases provide a factor of safety of not less than 2.0.

Because of the uncertainties regarding the longevity of the pipe, including the long term relationship between the pipe and the side wall stability, it is suggested the maximum height of cover over CIPP should be limited to fifteen (15) feet. Clearance from other utilities and structures should be as stated for CSP.

j. Corrugated Steel Pipe (Galvanized)

The minimum gage metal for corrugated steel pipe should be not less than 14 gage. The maximum design service life of corrugated steel pipe should normally be not more than fifty years, including protective coating unless steel shell thickness is increased accordingly. Flammable materials such as asphalt should not be permitted for use as a protective lining or invert paving. Concrete may be used as a protective lining (or for invert paving). However, the effective life of the lining or paving is uncertain due to loss of adhesion, spalling, or other factors. Consequently the flow capacity of the pipe should be determined on the basis of the unprotected corrugated steel, using an appropriate "n" value in the Manning formula (0.023 to 0.026). As noted previously in the section on Durability the estimated design service life for plain galvanized corrugated steel pipe may be estimated from the "years to Perforation Data" by Beaton and Stratfull[2]. It should be noted that the average life (years to perforation) determined from this source is one-half the average life given in Figure 5-4 of the AISI Handbook[29]. Corrugated steel pipe should not be installed in locations where a minimum width of undisturbed soil of two pipe diameters minimum (up to 12 feet maximum) of the storm drain cannot be maintained between the storm drain and other existing or proposed utilities or designated utility corridors. (This clearance may be reduced to one pipe diameter (up to 6 feet maximum) provided that all other utilities will be located not less than six vertical feet above the top of the storm drain. For depths of cover between fifteen feet (15') and twenty five feet (25') corrugated steel pipe may be used with a minimum thickness of steel of 10 gage, provided that other conditions such as 100 year design service life and adequate protection against abrasion and corrosion are provided for. Corrugated steel pipe should not be permitted in locations where the minimum soil resistivity is less than 3000 ohms-cm or the soil pH is less than 5.0, or where the storm water is anticipated to have a minimum resistivity less than 3000 ohms-cm or a pH less than 5.0.

E. ECONOMICS

1. Introduction

When alternate bids are taken for a project involving different materials, different costs, and different service lives, it becomes necessary to convert the first costs plus additional costs such as replacement costs over the design life of the project in order to equitably compare the alternate bids. This is usually accomplished by converting all costs during the service life of the project to present worth, called Least Cost Analysis.

The National Corrugated Steel Pipe Association issued a pamphlet[38] called "Least Cost Analysis". The opening paragraphs explain Least Cost Analysis as follows:

"Least Cost Analysis or Life Cycle Accounting is a technique that compares differing series of expenditures by restating them in terms of the present worth of the expenditures. In this way, competing designs which have differing cost expenditures at different intervals can be compared and the least cost design on a present worth basis chosen."

"The real difficulty with the method is making unbiased assumptions which produce fair comparisons of the alternate bids. The assumptions include project design life, project residual values at the end of its design life, material service life, rehabilitation costs and inflation and interest rates."

The American Concrete Pipe Association (ACPA) issued a bulletin[36] called "Bid Evaluation by Least Cost Analysis". The opening paragraph reads as follows:

"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. Most engineers are well acquainted with hydraulic and structural design criteria, but the effect of product durability on the total cost may not be clearly understood. On many projects when alternate materials are bid, selection is too often based on first cost. However, the alternate with the lowest 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."

2. Least Cost Analysis

The APCA bulletin further states:

"The factors which affect the analysis are:

Project design life

Material life

First Cost

Interest rate

Inflation rate

Replacement costs

Residual value costs

a. Project Design Life

The National Corrugated Steel Pipe Association Bulletin referenced above states as follows:

"Before any life cycle cost comparisons of materials can be made, the basic project design life must be established. In the case of some agencies it is already a matter of policy. For example, a 50-year design life for primary state highway culverts is common."

However, the bulletin referenced above by the American Concrete Pipe Association states as follows:

"Based on a review of published culvert surveys, the National Cooperation Highway Research Program Synthesis No.

50, "Durability of Drainage Pipe" defines service life as "the number of years of relatively maintenance-free performance", and further states "that a high level of maintenance may justify replacement before failure occurs." "The Synthesis offers guidelines to determine required project service lives for culverts under primary and secondary roads, with an appropriate safety factor. Based on these guide recommendations, Table 3 presents the number of years of relatively maintenance-free performance that should be required for culverts. As indicated, all sewers are classed as high type facilities, are located in urban areas with difficult construction requirements, and should be designed for 100 years of relatively maintenance-free performance.

Table 3. Project Design Life

Project	Design Life
Culvert, primary road	100 years
Culvert, secondary road	50 years
Sewer, all projects	100 years"

b. Material Service Life

This subject has been presented herein in the Section "DURABILITY" and therefore will not be repeated here.

c. First Cost

For evaluating alternate bids, first cost is the bid price submitted. A least cost analysis format may be included in the contract documents to make bidders aware of the basis for bid evaluation.

d. Interest Rate

The interest rate to be used to discount future costs to present worth is a matter of judgement. The usual financing method for city-financed storm drains is by means of general obligation bonds. Based on a historical record of average interest rates for G.O. bonds (available from U. S. Government), it is possible to make a reasonable projection for purposes of least cost analysis.

e. Inflation Rate

Like the determination of interest rate, the inflation rate is a matter of judgement. Historical data is available from the publications of the U. S. Government. The "Consumer Price Index" is frequently used to form a basis of inflation of replacement costs, although the "Producer Price Index" would probably present a better basis.

f. Replacement Costs

Replacement costs are commonly estimated on the basis of the bid tabulations, including all bid items that would be involved in the replacement, plus the cost of removing and disposing of the existing pipe, and the reshaping of the trench bedding area. It has been suggested[38] that corrugated steel pipe can be rehabilitated by means of invert repair. However, it is our opinion that when the invert shows perforations the structural adequacy of the pipe has been destroyed, and to rehabilitate the pipe would require, for example, a steel liner cylinder that would satisfy the original design requirements of structural adequacy and hydraulic capacity.

g. Residual Value

We would expect very few cases of a storm drain having a residual, or salvage, value. These would result, for example, when the material life is greater than the project design life, and the storm drain can continue to serve the project.

h. Formulations

The previously referenced ACPA Bulletin presents formulae for present worth analysis for three conditions. These are:

Case 1: Material life = Project design life

Case 2: Material life < Project design life

Case 3: Material life > Project design life

Case 1: Effective Cost = Bid price.

$$EC = P$$

Case 2: Effective Cost = bid price plus the present value total of all replacement costs adjusted for inflation.

$$EC = P \left[1 + \left(\frac{(1 + I)}{(1 + i)} \right)^{n} + 3 \times \left(\frac{(1 + I)}{(1 + i)} \right)^{mn} \right] *$$

Case 3: Effective Cost = bid price minus the residual value remaining at the end of the project design life.

$$EC = P \left[1 - \left(\frac{n - np}{n} \right) \left(\frac{(1 + I)}{(1 + i)} \right)^{np} \right]$$

where : EC = Effective Cost

P = Bid price

I = Rate of inflation

i = Interest rate

n = material life, years

m = Total number of pipe replacements

Np = Project Design Life, years

* Note: In Case 2 the number of $\left(\frac{1 + I}{1 + i}\right)$ terms should equal the number of replacements, with the exponent increasing from n, 2n, etc. to mn.

RECOMMENDATIONS

A. DESIGN SERVICE LIFE

Establish a City of Phoenix policy relating to design service life of all storm drains as follows:

1. The minimum design service life for all storm drains shall be fifty (5Ø) years.

2. The minimum design service life for storm drains shall be one hundred (1ØØ) years under any of the following conditions:

   a. Located within the right of way of a major arterial street (e.g. one-mile and half-mile grid streets, parkways, and others as determined by the City Engineer).

   b. The height of cover is in excess of fifteen (15) feet.

   c. Storm drains which are to be located adjacent to or between structures which are located horizontally a distance equal to or less than the depth of pipe cover from the structure to the center line of the pipe.

   d. The storm drain is to be designed to operate under a pressure head.

B. DESIGN CRITERIA

Establish design criteria for the various pipe materials for storm drains as follows:

1. General

   a. Storm drains should be limited to a maximum cover depth of fifteen (15) feet. Depth of cover more than fifteen (15) feet may be permitted in cases of necessity, i.e., no viable alternative, but only with the approval of the City Engineer.

b. Storm drains which will have more than twenty-five feet (25') of cover should be designed with a service life of 100-years minimum and sized to permit the installation of a metal plate liner which will carry the design flow and retain full structural strength.

c. The unit earth load and minimum D-load should be stated for each type of pipe.

2. Reinforced Concrete Pipe

   a. Suitable for 100-year plus design service life with the following limitations:

      i. For anticipated water pH of 5.0 or less the storm drain should be either invert paved or fully lined with an acceptable liner. Flammable lining material should not be used.

      ii. For soil pH of 5.0 or less the storm drain should be given a protective coating.

      iii. For high sulfate levels in soil or in storm runoff, Type V cement should be used in place of Type II.

3. Cast-in-Place Concrete Pipe

   a. The maximum height of cover over a cast-in-place concrete pipe (CIPP) should be limited to fifteen (15) feet.

   b. CIPP should only be permitted for use in soil materials which have a Proctor Density of ninety (90) percent or higher.

   c. The material on which and in which the pipe is to be constructed should be stable and unyielding when saturated, and non-expansive.

d. The design stresses for CIPP should provide a factor of safety of not less than 2.0.

e. CIPP should not be installed in locations where a minimum width of undisturbed soil of two pipe diameters minimum (up to 12' maximum) of the storm drain cannot be maintained between the storm drain and other existing or proposed utilities or designated utility corridors.

4. Corrugated Aluminum Pipe

(Not addressed in this evaluation.)

5. Corrugated Steel Pipe (Galvanized)

a. The minimum gage metal for corrugated steel pipe shall be 14 gage.

b. The maximum design service life of corrugated steel pipe shall be fifty years, including protective coating.

c. The use of flammable linings on corrugated steel pipe will not be permitted.

d. Concrete may be applied as an inner lining to corrugated steel pipe for abrasion protection. However, because the effective life of the concrete lining is uncertain, the flow capacity of the pipe shall be determined on the basis of the corrugated pipe only, without lining, using a higher appropriate "n" value in the Manning formula.

e. The estimated design service life for plain galvanized steel storm drain should be taken as one-half (1/2) the value derived from Figure 5-4, page 239, of AISI Handbook of Steel Drainage and Highway Construction Products, Third Edition 1983.

f. Corrugated Steel Pipe should not be installed in locations where a minimum width of undisturbed soil of two pipe diameters minimum (up to 12' maximum) of the storm drain cannot be maintained between the storm drain and other existing or proposed utilities, or designated utility corridors.

The above limitation may be reduced to one pipe diameter minimum (up to 6 maximum) provided the other existing utility is not less than 6 feet vertically above the top of the storm drain.

g. For depths of cover between fifteen (15) feet and twenty five (25) feet, corrugated steel pipe may be used with a minimum thickness of steel of 10 gage, providing other conditions such as 100-year service life and protection against abrasion and corrosion are adequately provided for.

h. Corrugated steel pipe should not be installed in locations where the minimum soil resistivity is less than 3000 ohms-cm and the soil pH is less than 5.0, or where the storm water is expected to have resistivity and pH less than 3000 ohms-cm and 5.0 respectively.

i. Corrugated steel pipe should only be permitted for use in soil materials (the undisturbed trench sidewalls) which are at a Proctor Density of ninety (90) percent or higher, unless allowable design stresses are proportionately reduced.

j. The allowable design stresses for corrugated steel pipe should provide a factor of safety of not less than 2.0.

C. OTHER RECOMMENDATIONS

1. The contract specifications should clearly define causes for rejection of individual pipe sections: 1) at the place of manufacture; 2) at the job site; and 3) in the trench. (For example, excessive cracking of concrete [concrete pipe or concrete lining] is undesirable. Provide the manufacture, contractor and field inspector clear specifications as to what is cause for rejection.)

2. It is recommended that the City of Phoenix review and revise their specifications for bedding and backfill of storm drains. The most critical area is to provide uniform bedding from the invert level (including haunch areas) to a level one foot above the top of the pipe. The bedding should be compacted in controlled lifts to not less than 90% Proctor Density. Compaction by manual and pneumatic tampers is the preferred method. If safety conditions preclude the use of this method some other means must be provided. Other means include water jetting plus vibration which is not desirable but acceptable if no more appropriate method is available. Another possible method which has been suggested is to use either new or used seal "chips" compacted in layers with vibration.

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