

# Abrasion Resistance of Aluminum Culvert Based on Long-Term Field Performance

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Culvert pipes not only are placed to drain water but are required to carry bed load materials including rocks. The flow and energy characteristics of bed load materials and their effect on culvert pipes are not well understood. Analysis of mechanics can provide a format for comparing predicted characteristics with field experience data, and results confirm the validity of the assumptions. In 1968 an initial study was reported on 229 aluminum culverts that had been exposed to abrasion for from 4 to 7 years. That study proposed a form of energy level for bed load materials and rated the abrasion performance of aluminum culvert through a series of energy ratings. The energy level and abrasion predictions were compared with actual field experience, and long-term culvert abrasion can be predicted when culvert geometry, installation arrangement, and content of bed load materials are established. In 1984 and 1985 the field experience of the originally reported culvert group averaged 20 years of exposure to abrasion. In this paper are presented the results of the 1984–1985 study. The basic method of determining abrasion energy levels has been retained and simplified to emphasize key variables that affect abrasion. The 1985 study indicates that abrasion of aluminum culvert follows the patterns of the previous work. Long-life abrasion typically does not continue at a linear wastage rate but levels off to a much reduced rate, reflecting reductions in total energy as the flow channel stabilizes with age. Abrasion and service life for aluminum culvert inverts may be predicted as a function of water flow, culvert entrance arrangement, culvert slope, and rock content of streambed load.

There have been few comprehensive studies on the resistance of metal culvert pipe to abrasion caused by normal streambed loads. Shortly after commercial introduction of aluminum alloy culvert in 1960, laboratory sample abrasion tests were conducted by several state highway departments. These tests resulted in selective agency specifications restricting the use of metal culvert, generally by limiting water velocity only. One such specification limited use of aluminum culverts to a maximum entrance velocity of 5 ft/sec and recommended increasing steel culvert thickness when the water velocity exceeded 5 ft/sec (1).

A detailed study of aluminum alloy culvert in locations subject to abrasion was reported by Koepf in 1968 (2). In that report abrasion service life of aluminum pipe was discussed in terms of bed load energy levels and visual ratings for 229 aluminum culverts that had been in service for approximately 5 years. Velocity–impact energy relationships were developed, and abrasion ratings were established using visual rating and invert sample coupons. These were tabulated so that the culvert design engineer could relate predicted service life to abrasion-related conditions for proposed pipe installations.

The present study, some 15 years later, provided the opportunity to field inspect many of the original aluminum culverts that were in the 1968 test and thus extend actual service life data from 5 years to 20 years or more. In this paper are presented the results of the field inspections, abrasion ratings, and culvert invert metal-

lographic cross sections. The results are compared with the 1968 results. The original formulas and relationships for determining impact energy and impact energy-to-velocity ratio are discussed and trends are compared.

The 1968 study was arranged to present the characteristics of aluminum culvert abrasion through a series of steps intended to describe bed load behavior and performance due to abrasion and match observed behavior to predictions. The steps are as follows:

1. Describe the long-term erosion-corrosion cycle in the presence of abrasive water flow causing wastage of aluminum surfaces and compare it with the same cycle causing wastage of galvanized steel surfaces.
2. Apply the mechanics of erosion to culvert including bed load material, culvert size, culvert slope, and resulting water and rock velocity to produce a form of bed load kinetic energy levels. Field observations were made of rock flow in culvert to confirm the validity of the bed load kinetic energy method as a means of predicting aluminum alloy culvert service behavior.
3. Undertake field investigation of approximately 200 aluminum alloy culverts located in abrasive exposures, report performance, and compare with predicted behavior.

## EROSION-CORROSION CYCLE

Aluminum alloys develop corrosion resistance through maintenance of an aluminum oxide layer covering all exposed surfaces. The oxide layer is very thin, is substantially colorless, promptly restores itself when abraded off, is very tough, is adherent, and resists removal. Culvert sites that are considered abrasive do not normally contain water compositions that are extremely acidic or alkaline or any combination that is expected to be corrosive to aluminum (3). Because the abrasive bed load is chemically inactive, abrasive sites are not corrosive sites for aluminum alloy. Consequently, loss of metal from aluminum alloy culvert becomes dependent on abrasion energy without the addition of corrosion effects.

Galvanized steel exposed to an abrasive flow follows an entirely different form of erosion-corrosion cycle. The abrasive action of the bed load flow removes the relatively soft zinc and zinc oxide coating and exposes the steel surface below. The rate of removal will depend on the frequency of bed load flow. When the steel surface has been exposed, iron oxide is then promptly formed. Iron oxide is not highly abrasion resistant and will be removed by further abrasive flow, reexposing the steel continuously for more oxide formation. This progressive mechanism of erosion-corrosion causes small but steady rates of wastage of steel culvert inverts. The long-term wastage rate on the average steel culvert appears to be governed more by the corrosion portion of the erosion-corrosion cycle than by abrasion. The progressive erosion-corrosion cycle proceeds on steel with all types of bed load flow including sand and gravel. In cases in which water may be acidic and

corrosive, wastage rates increase. The mechanism of wastage is frequently expressed in inches per year loss, which results in a lineal form for predicting steel culvert invert service life.

A generalized cumulative erosion-corrosion curve is shown in Figure 1 to illustrate the observed characteristic combined metal wastage patterns of both aluminum alloy and galvanized steel culvert.

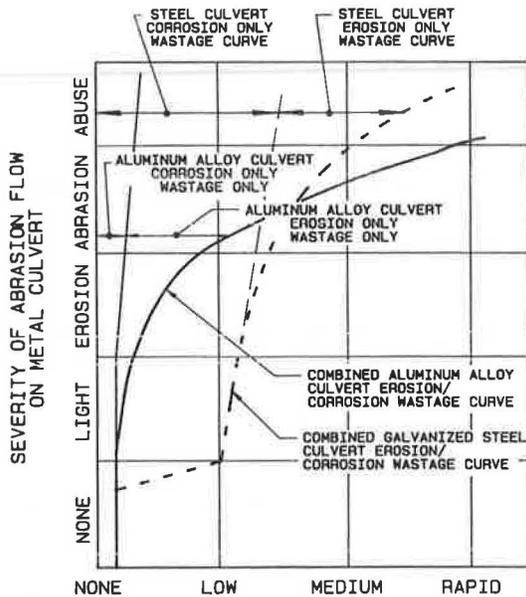


FIGURE 1 Representative rate of wastage of culvert pipe metal from an erosion-corrosion cycle.

Protective coatings are sometimes applied in abrasive site applications to extend service life. Culvert life may be lengthened only to the extent of the added resistance and integrity of the coating, and because the most common coatings are not highly resistant to abrasion the value of these coatings on either aluminum alloy or steel culverts is limited (4, 5).

### MECHANICS OF ABRASION APPLIED TO ALUMINUM ALLOYS

Surface abrasion on the invert of aluminum alloy culverts is the result of cumulative impact or scrubbing action by particles of hardness equal to, or greater than, the resistance of the aluminum oxide-protected metal surface. To evaluate or predict bed load abrasion it is desirable that abrasive action be reduced to a mathematical model. Observations show that culverts subjected to active flow are self-scrubbing (i.e., self-cleaning) including cleaning corrugation valleys so that buffer layers or smooth-line inverts are not established. Field observations of aluminum culvert installations show light peening and no significant evidence of abrasive metal wastage caused by sand or very small rock flows. Flows that contain increasing quantities and sizes of rock show increasing surface abrasion, peening, scarring, and ultimately metal wastage. From this it may be concluded that severity of abrasion is directly related to the cumulative kinetic energy of the bed load material rocks expressed as equivalent mass and velocity.

Figure 2 shows the force path of a single rock as it progresses through a culvert. When the driving force of water pressure

exceeds the net resistance of gravity and friction of the example rock it will move and, when clear of the corrugation, continue to accelerate to a terminal velocity ( $U$ ). Because culvert inverts are not smooth but a series of corrugated ridges, the actual path of a rock has been observed to follow a series of impact cycles as shown in Figure 2. During the initial portion of a flow cycle the rock is accelerated up the corrugation incline, moves within the water flow for one to several corrugation lengths, and then drops to strike the next corrugation incline, where impact reduces the rock velocity. A repeating cycle is obtained. The form of an abrasion energy level can be described by the equation

$$KE_u = (W/2g)U^2 \quad (1)$$

where

$$KE_u = \text{kinetic energy of the "statistical" rock representing the bed load material in the foot-pounds,}$$

$$W = \text{weight of statistical rock in pounds,}$$

$$g = \text{acceleration due to gravity (32.2 ft/sec}^2\text{), and}$$

$$U = \text{average velocity of rock in culvert (ft/sec).}$$

For a typical statistical rock of spherical shape weighing 150 pounds per cubic foot, the kinetic energy can be rewritten as

$$KE_u = 0.00071 d^3 U^2 \quad (2)$$

where  $d$  is rock diameter in inches.

The practical use of kinetic energy level as a means of describing abrasion levels must include a number of dimensional assumptions to streamline the form of solution. For example, a rock may be considered a sphere of uniform density, energy is expressed in translation motion, the most common culvert corrugation is 2 2/3 in. pitch by 1/2 in. height, and the rock velocity is the overall average time between impacts on the length of the culvert divided by the time to pass through.

### Rock Size, Shape, and Availability

A basic assumption of the 1968 analysis was that progressive abrasion will follow a generally linear time rate pattern that reflects a uniform flow of bed load and rock sizes. Comparison of 20-year service data in the 1985 study with 5-year service data of the 1968 study shows that abrasion rates in average installations diminish. This is due principally to reduced number and sizes of available rock flow as the upstream drainage channels stabilize with age. Unfortunately, abusive and highly abrasive sites do not diminish substantially because their channels do not tend to stabilize.

The 1985 field investigation program also established that abrasion results are independent of geographic location as long as rock size, culvert size, and slope are similar. There are variations due to rock shape, hardness, terrain, and rainfall; however, variations are not excessive. These variations are patterned after routine observations of culvert in most geographic areas of the United States. Examples follow.

1. Areas with considerable vegetative ground cover restrict rock flow and thus cause less abrasion. Increased abrasion can be expected in areas with little ground cover and ample loose rock on the slopes.
2. Abrasion may be slightly greater than average in areas of consistent rainfall, steep slopes, and hard rocks with irregular shapes.

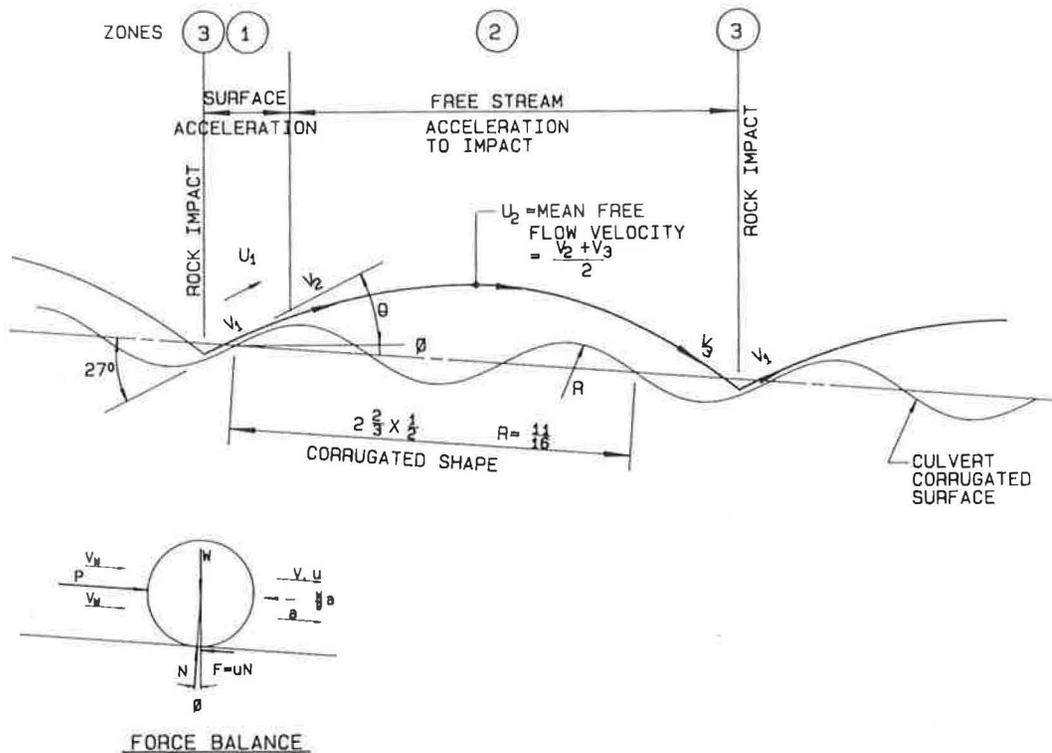


FIGURE 2 Representative rock cycle path.

The control culverts used for study are concentrated in the Pacific northwest, the California High Sierras, and northern New York and New Hampshire, which represent high expectations of abrasion. Where few rocks are naturally present, significant abrasion of aluminum alloys is not expected and has not been observed.

**Velocity**

The analysis is particularly dependent on the velocity of the rock, because the kinetic energy form contains a squared velocity term. Consequently, to best describe the velocity, it is necessary to review the different velocities that occur in specific locations of a typical culvert installation.

1. Culvert entrance water velocity ( $V_e$ ) is the average velocity at the cross section entrance to a culvert. Entrance velocity is limited by upstream water level, culvert diameter, and geometry of the entry. Entrance water level usually governs the flow capacity of the installation. Designers frequently use flooded entrance water level flow calculations as a guide to selection of culvert size. Entrance velocity is not a satisfactory method of defining water velocity for establishing abrasion ratings because it does not describe actual water or rock velocity through the culvert.

2. Pipe water velocity ( $V_p$ ) is the velocity of the water through the culvert after it has cleared the culvert entrance and is considerably higher than culvert entrance velocity. It is a function of culvert diameter, culvert slope, and corrugation shape. As an example, a 48-in. culvert with a flow of 63 ft<sup>3</sup>/sec with a flooded projecting square entrance will develop an entrance velocity of 5.0 ft/sec and a pipe velocity of 13 ft/sec with a 21-in. depth on a 5 percent culvert slope, or 24 ft/sec with a 13-in. depth on a 30 percent culvert slope. Pipe velocity best describes the level of

expected rock flow energy that can cause abrasion to culvert inverts.

3. Mean pipe water velocity ( $V_w$ ) as defined for this study is the water velocity in a culvert for a water flow through a square end entrance ponded at half the depth of the culvert. This is a compromise velocity used to represent a reasonable combination of frequency of occurrence and velocity magnitude and is used in this study to establish rock kinetic energy levels. Design water velocity values for typical culvert sizes and slopes are given in Table 1.

4. Rock velocity ( $U$ ) is the average velocity of a rock from entry to exit as it passes through the culvert when subjected to a forcing flow due to water velocity. The rock velocity may vary from zero, when water velocity is not sufficient to keep the rock moving or at an instant of total stopping impact, to approaching

TABLE 1 MEAN PIPE WATER VELOCITY (feet per second)

Diameter of Culvert (in.)	Water Flow, <sup>a</sup> Q (ft <sup>3</sup> /sec)	Culvert Slope (%)					
		5	10	15	20	25	30
18	2.0	5.5	6.6	7.6	8.3	9.1	10.0
24	4.4	6.2	8.0	9.3	10.6	11.5	12.0
30	8.0	7.2	9.4	10.7	12.0	12.8	14.0
36	13.0	8.0	10.3	12.0	13.5	14.2	15.1
42	20.0	10.0	12.0	14.0	15.1	16.5	17.8
48	29.0	10.1	13.5	15.0	16.5	18.0	19.5
60	52.0	11.7	15.5	17.5	20.0	21.7	23.0
72	83.0	13.2	17.0	20.0	21.3	24.0	25.5
84	130	14.8	19.0	21.5	24.0	26.0	27.7
96	186	16.0	21.0	24.0	26.8	29.0	31.0

<sup>a</sup>Flow in cubic feet per second is based on square projecting entrance half full ( $H/D = 0.5$ ). The velocity of the flow at indicated slope is based on Manning's equation with  $n = 0.024$ .

water velocity as if there were no impacts to slow it down. The ratio between rock velocity and pipe water velocity was determined from field tests by timing average rock velocity in culvert water flows. An empirical factor  $(1 - e)$  may be added to the energy equations to relate mean rock velocity to water velocity. Field observations indicated that rock velocity peaked at about 83 percent of water velocity, which limits  $e$  to 0.17 minimum. This factor provides a means of describing the observed reaction of abrasion as culvert slope and rock sizes are reduced. Further, to focus on typical expected energy levels, it can be reasoned that small maximum rock sizes are typically found in smaller culvert installations and larger maximum rock sizes are found in larger culverts. These approximations and empirical data show that average water velocity can be related to a specific peak rock size and culvert installation slope. For this study, 2-in. peak rocks are matched to 18-in.-diameter culverts, and sizes are increased to 12-in. rocks for 60-in.-diameter culverts. Deviations in pipe water velocities related to culvert sizes are consistent with the other assumptions.

**Mean Impact Energy**

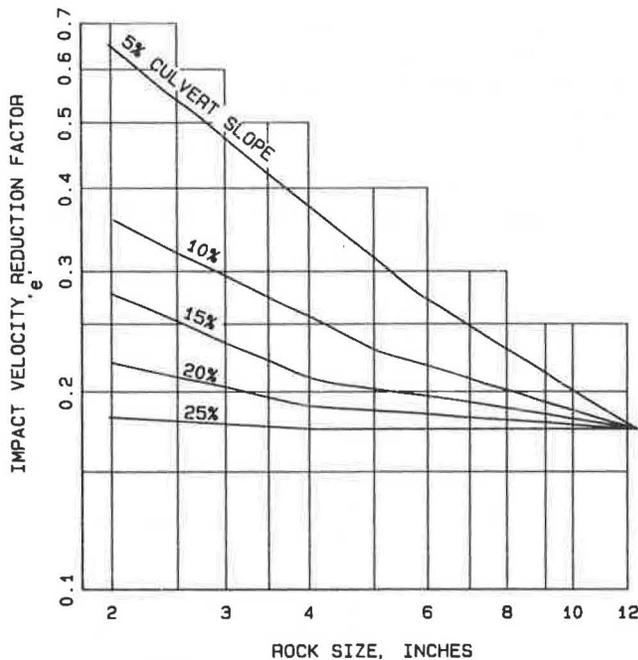
The kinetic energy level of a single spherical shaped rock available for impact as it passes through the culvert is represented by

$$KE = 0.00071 d^3 V_w^2 (1 - e)^2 \tag{3}$$

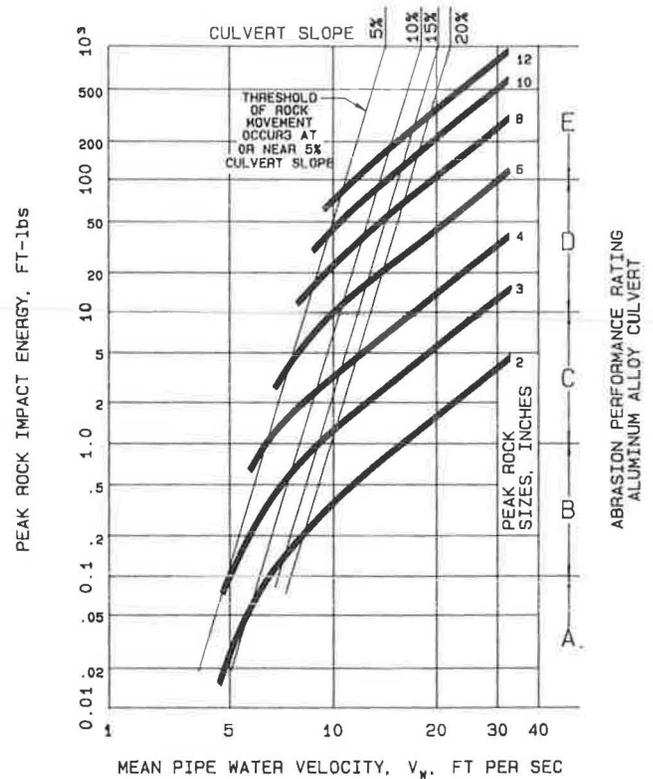
where  $e$  is a field-determined empirical factor from at rest to maximum velocity and is a function of rock size and pipe slope (Figure 3).

The total kinetic energy to which a culvert invert surface may be subjected over a long period of time can be considered proportional to such a unit rock equation.

The resulting composite rock energy equation is plotted in Figure 4. The lower cut-off line approximates the minimum flow



**FIGURE 3** Field-determined impact velocity reduction factor versus rock size and culvert slope.



**FIGURE 4** Rock energy curves.

and culvert slope necessary to maintain a given rock movement, generally with a threshold at 5.0 percent culvert slope.

Figure 4 also includes a series of abrasion ratings established from energy calculations and the observations from the 1968 survey. The observed levels were generally confirmed by the 1984 study. These rating levels serve as a basis for performance predictions. These data are also shown in tabular form in Table 2.

**FIELD INVESTIGATION OF ALUMINUM ALLOY CULVERT SITES**

The group of culverts selected for the 1968 abrasion report with an average of 4 to 5 years' service was reinspected during 1984 and

**TABLE 2** SELECTED ABRASION RATING LIMITS FOR INDICATED ROCK SIZES AND CULVERT SLOPE

Abrasion Rating Limit	Rock Size <sup>a</sup> (in.)	Maximum Slopes (%) for Typical Culvert Sizes		
		24 in.	48 in.	72 in.
B	2	45	30	13
	3	20	5	5
	4	5	5	5
C	4	45	30	14
	6	25	10	5
	8	15	5	5
D	6	—	40	35
	8	—	30	15
	10	—	12	6

Note: Energy level predictions are those of Figure 4. Threshold of rock movement is approximately 5 percent.  
<sup>a</sup>Statistical peak rock size expected.

1985 to obtain field data on culverts with an average service life of 20 years.

Some culverts are no longer in service as a result of road relocations or modifications or washouts, and some were not inspected. Approximately 77 percent of the 1968 group were reexamined. A selected number of additional culverts in abrasion sites with less than 20 years in service were added to this study to fill out the original control group. The field investigation group was thus 186 culverts.

The 1968 study used the control group as a basis for developing a suggested culvert abrasion rating performance system. This original rating system related experience to that date to equivalent wastage rates expressed in inches per year in an attempt to compare with typical forms of expressing corrosion rates. When the 1984 study compares 5-year exposure with 20-year exposure the results indicate that abrasion of aluminum culvert does not progress at a linear wastage rate but that total abrasion levels off at a much reduced rate. This reflects reduced cumulative impact energy from fewer rocks each season because of gradually stabilizing upstream channels. Because of this, the abrasion rating schedule description suggested for the 1968 study has been revised in the 1984 study by eliminating the lineal wastage factor. The revised schedule is given in Table 3. With 20 years of experience as support, generalized projected culvert service life data have been suggested in the abrasion rating schedule.

**Culvert Inspection Procedure**

The method of examining and sampling used previously was repeated in the 1984 survey. Each culvert site inspected was given an in-place overall visual abrasion rating from Table 3, using abrasion rating schedule letters A through E to represent severity of abrasion site. The original rating levels were used arbitrarily to describe observed conditions. Subsequent analysis and observed conditions made the ratings generally reproducible. Peak rock size was determined in the field by visual inspection of the streambed and the culvert inverts. Size was selected to represent not the

largest possible rock to pass through but the estimated largest "statistical" rock that may pass through the culvert repeatedly at a "significant" frequency during periods of substantial water flow. This size selection is intended to represent the size typical of 25 percent of the rock flow is approximate only, but is important and calls for the exercise of judgment to simulate the exposure to abrasion expected over many years. Observations have suggested that a peak rock size of some frequency would not exceed 8 in. This approximation is necessary to the rating and it proved to be manageable with some experience.

Culverts were also sampled by drilling out 1-in.-diameter coupons from the invert crowns and subjecting them to laboratory examination. Each separate culvert or culvert group with similar exposure was sampled. Coupons were cleaned and surface photographed at 2.5X, then cross sectioned, mounted, etched, and photomicrographed at 5X. These photographs permitted a more detailed examination of surface and cross section to confirm the on-site visual abrasion ratings. Not all culverts were sampled, and actual coupons selected for photomicrographs are representative of examples of each abrasion rating. Field investigation showed that abrasion on aluminum culvert is generally limited to the upstream portion of the crown radius of the corrugations in the area of the invert line only.

Background data containing visual abrasion ratings for the 1967-1968 and the 1984-1985 inspections are available from the author.

**RESULTS AND DISCUSSION**

Figures 5-12 show examples of abrasion ratings A through E, including the abrasion test sites of both the 1968 and the 1984-1985 studies. In some instances the same pipe was not inspected, but a similar nearby pipe in the same exposure was selected to log the observed abrasion ratings. Figure 13 shows the observed effect of abrasion wear on fasteners.

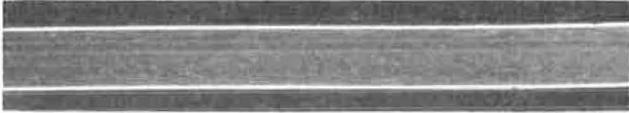
A cross section rated A shows no effect of abrasion. The photos show the thin layer of the aluminum cladding alloy 7072 on both

**TABLE 3 ABRASION PERFORMANCE RATING SCHEDULE FOR ALUMINUM ALLOY CULVERT PIPE**

Performance Zone Rating	Effect on Surface of Crown of Corrugation, Invert Only <sup>a</sup>
A	No surface effect; no reduction in service life due to bed load; abrasion service life 100 years
B	Nonerosive; some slight roughening of the metal surface but no metal removal by erosion action; no reduction in normal service life of aluminum culvert; projected abrasion service life 75 years or more
C	Erosion; surface roughening and slight progressive removal of metal from culvert; some gouging may be noted if rocks tend to be large; projected abrasion service life 50 years or more
D	Abrasion; surface roughening and slow removal of metal from culvert; definite reduction in pipe life due to abrasion; gouging of surface may be expected; projected abrasion service life 25 to 50 years
E	Abusive; surface roughening and rapid removal of metal from culvert; definite reduction in pipe life due to abrasion; projected abrasion service life 25 years or less

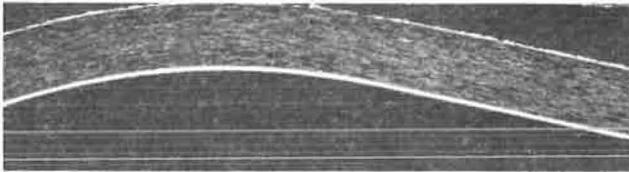
<sup>a</sup>Abrasion effects only this portion of the surface. The remainder of the culvert is usually unaffected by abrasion.

ABRASION RATING A  
 ALUMINUM ALLOY ABRASION SIDE UP  
 CLADDING ON TYPICAL FOR ALL  
 BOTH SIDES SECTIONS



EXAMPLE SECTION  
 1968 STUDY (67-330 SHOWN)  
 (5X MAGNIFICATION)

ABRASION RATING B



EXAMPLE SECTION  
 1984 STUDY  
 (84-085 SHOWN, SAME AS 67-354)  
 (5X MAGNIFICATION)

FIGURE 5 Photomicrographs of abrasion ratings A and B (sample sections).

sides of the 3004 core alloy. Cladding is galvanically anodic to the core making it sacrificial in a corrosive environment. When corrosion is encountered it will usually be limited to the cladding thickness. The nominal cladding thickness is 5 percent of the total thickness on each side. For 16-gauge culvert pipe of 0.060 in. total thickness, the cladding thickness is about 0.003 in. on each surface. The cladding alloy is slightly softer than the core alloy.

The "nonerosion" rating (A/B or B) samples show characteristic light surface pebbling but not significant removal of cladding. There is virtually no loss of culvert metal or strength.

The "erosion" rating (B/C or C) samples show the same pebbling texture plus a superimposed light random gouging from larger rock to a degree sufficient to visibly disturb and gradually remove metal. The long-term metal loss is small.

The "abrasion" rating (D) sample represents the cumulative result of pebbling and substantial gouging, which gradually reduces the overall metal thickness by removal. Long-term metal loss is significant and does limit expected culvert life.

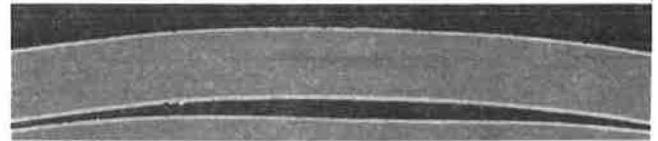
The "abusive" rating (E) sample shows more rapid progressive removal of culvert invert metal by gouging and pounding than for abrasive rating D. Abusive energy levels can be large enough to wear through or flatten corrugations as part of the wastage process. Rivet projections are particularly vulnerable in abrasive and abusive flow and are rapidly worn flush where they project above the crown of the invert. Fortunately, the loss of an occasional rivet head in the invert area does not cause overall culvert distress once culverts are bedded. There are few sites that can qualify as abusive, and in such locations all pipe materials—aluminum, steel, and concrete—have been observed to deteriorate rapidly.

## CONCLUSIONS

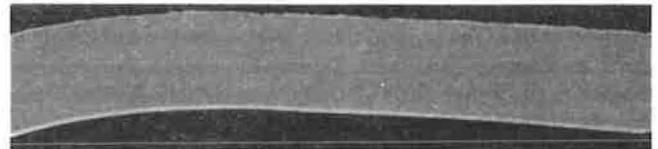
Aluminum alloy culvert has been shown by observation and analysis of the control group of culverts to be resistant to abrasion by bed load materials in culvert water flow. The abrasion rate of aluminum alloy culvert is not linear but decreases with time as demonstrated by the small changes in condition between the 1968 study and the 1985 study. Considering abrasion only, service life of aluminum alloy culverts can be related to rock impact energy levels, expressed by ranges of the abrasion rating schedule. The abrasion rating schedule ranges can be related to expected water flow, culvert entrance arrangement, culvert slope, and expected rock content in bed loads.

## RECOMMENDATIONS FOR ESTIMATING SERVICE LIFE USING ENERGY CURVES

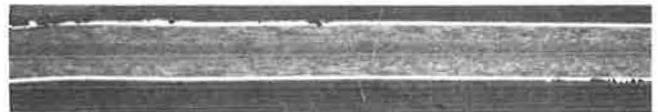
The established mathematical kinetic energy levels, substantiated by confirming field data, can be used as a basis for designing



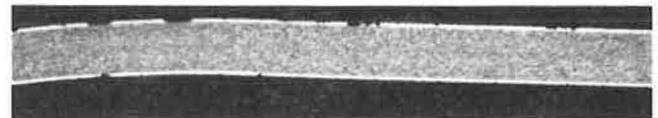
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 1967 STUDY (67-267)  
 (5X MAGNIFICATION)



EXAMPLE SECTION  
 1967 STUDY (67-310)  
 (5X MAGNIFICATION)

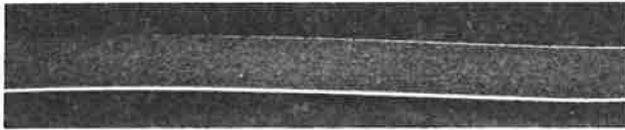


EXAMPLE SECTION  
 1984 STUDY (84-036)  
 (5X MAGNIFICATION)



EXAMPLE SECTION  
 1984 STUDY (84-081)  
 (5X MAGNIFICATION)

FIGURE 6 Photomicrographs of abrasion rating B/C (sample sections).



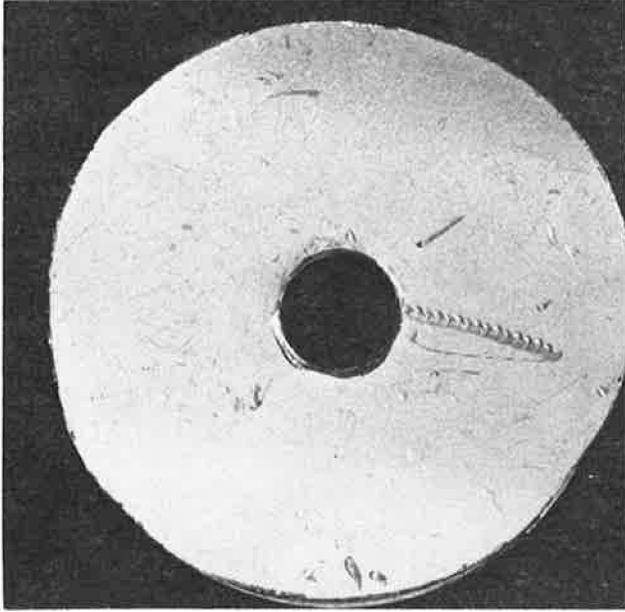
EXAMPLE SECTION  
1984 STUDY (84-072)  
(5X MAGNIFICATION)

SITE 84-072 RATED B/C

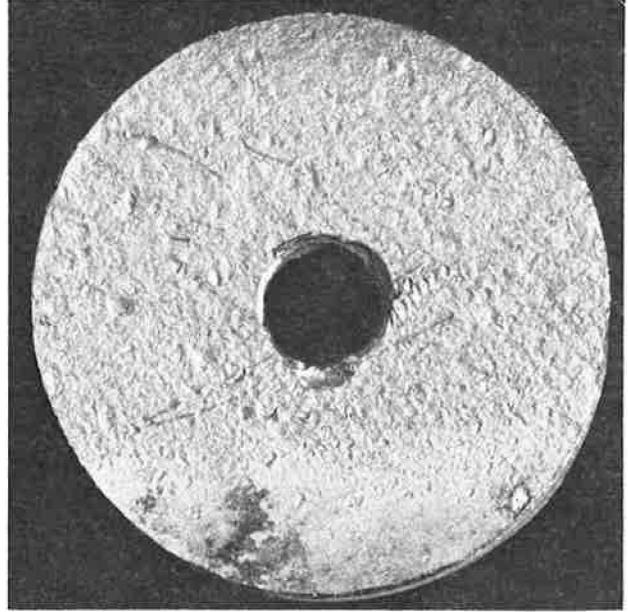


EXAMPLE SECTION  
1984 STUDY (84-032)  
(5X MAGNIFICATION)

SITE 84-032 RATED B/C



EXAMPLE FACE  
1984 STUDY (84-072)  
(2.5X MAGNIFICATION)

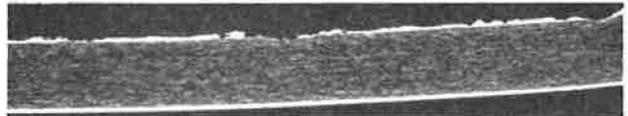


EXAMPLE FACE  
1984 STUDY (84-032)  
(2.5X MAGNIFICATION)

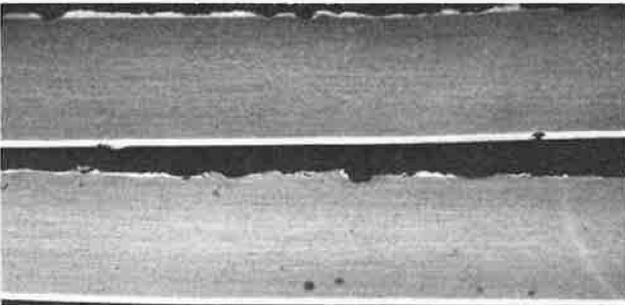
FIGURE 7 Photomicrographs of abrasion rating B/C (sample sections and faces).



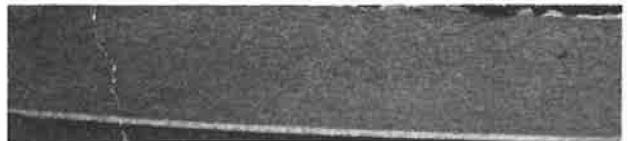
EXAMPLE SECTION  
1967 STUDY (67-316)  
(5X MAGNIFICATION)  
RATING B/C



EXAMPLE SECTION  
1984 STUDY  
(84-044 SAME AS 67-316)  
(5X MAGNIFICATION)



EXAMPLE SECTION  
1967 STUDY (67-326, 327)  
(5X MAGNIFICATION)



EXAMPLE SECTION  
1984 STUDY  
(84-079, SAME AS 67-326)  
(5X MAGNIFICATION)

FIGURE 8 Photomicrographs of abrasion rating C (sample sections).



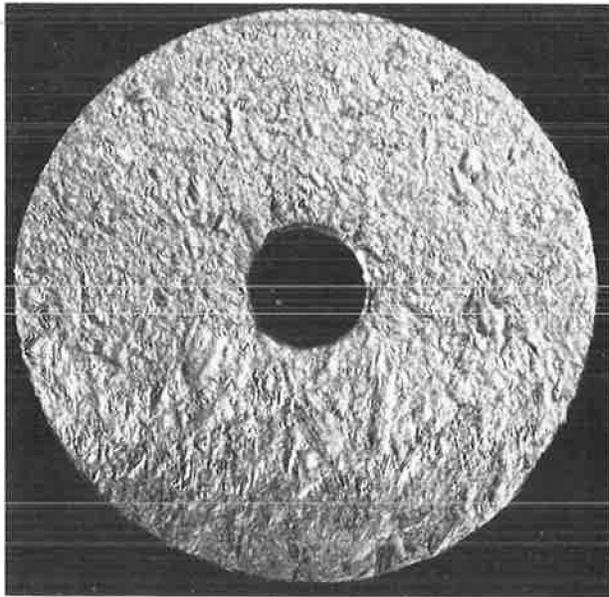
EXAMPLE SECTION  
1984 STUDY (84-049)  
(5X MAGNIFICATION)

SITE 84-049 RATED B/C

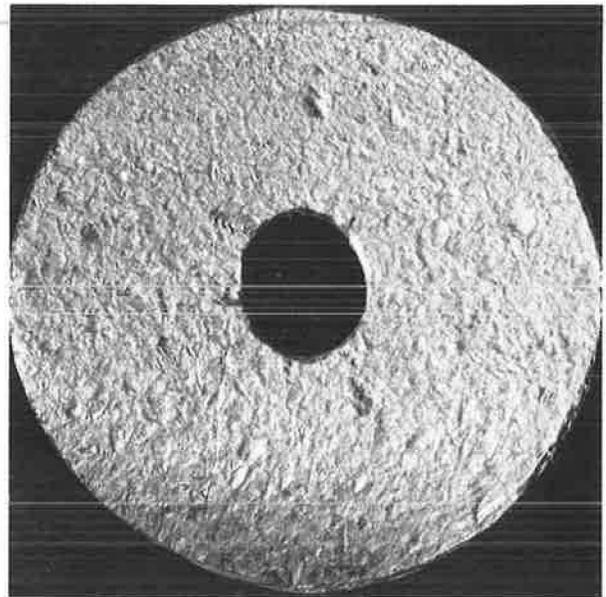


EXAMPLE SECTION  
1984 STUDY (84-021)  
(5X MAGNIFICATION)

SITE 84-021 RATED C



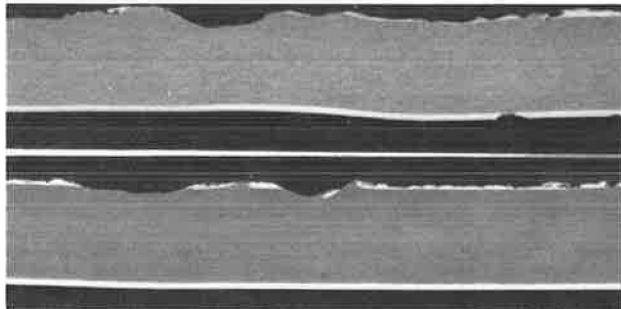
EXAMPLE FACE  
1984 STUDY (84-049)  
(2.5X MAGNIFICATION)



EXAMPLE FACE  
1984 STUDY (84-021)  
(2.5X MAGNIFICATION)

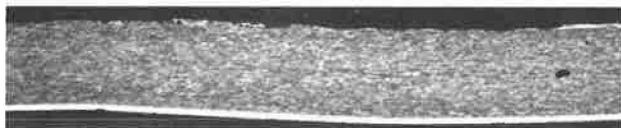
FIGURE 9 Photomicrographs of abrasion rating C (sample sections and faces).

SITE 67-319 RATED D



EXAMPLE SECTION  
1967 STUDY  
(67-319 SAME AS 84-046)  
(5X MAGNIFICATION)

SITE 84-046 RATED C



EXAMPLE SECTION  
1984 STUDY  
(84-046 SAME AS 67-319)  
(5X MAGNIFICATION)

FIGURE 10 Photomicrographs of abrasion rating D (sample sections).

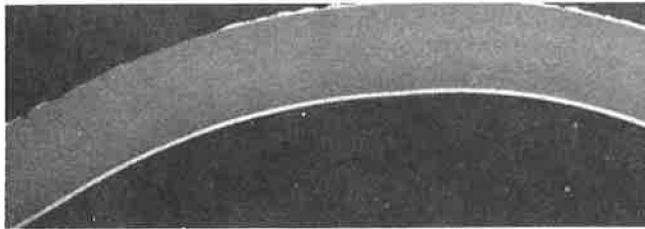
aluminum alloy culvert for abrasive conditions. Table 2 combines a series of culvert sizes, culvert slopes, and peak rock sizes that are representative of each abrasion rating level. Using these data from the current study, which represent more than 20 years of field service, a projected abrasion service life expectation can be added (Table 3).

Expected service life of a new installation can be predicted by determining the abrasion rating level by assessing the upstream bed load, maximum rock size expected, culvert size, and culvert slope. Figure 4 can be used to approximate the culvert abrasion rating. For example, a 36-in. culvert placed at a 15 percent slope develops an energy water velocity of 12.0 ft/sec according to Table 1. When these data are plotted on Figure 4 and peak rock size of 6 in. is selected, a D abrasion rating is indicated with a suggested service life of from 25 to 50 years.

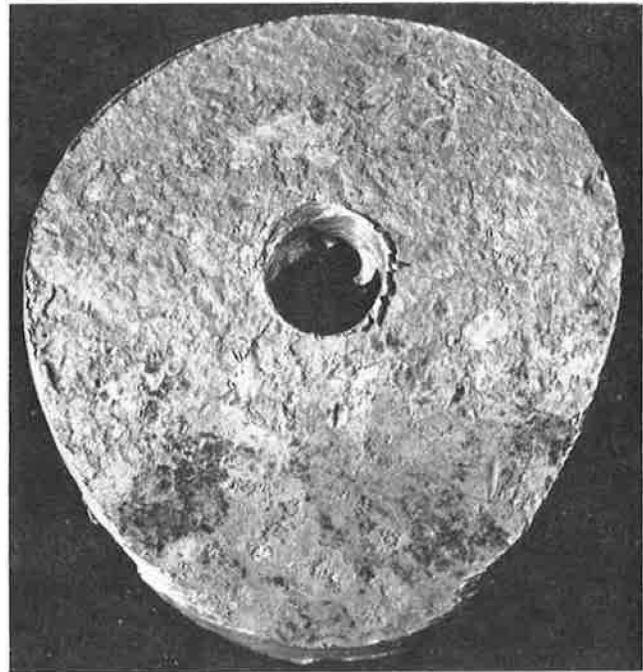
In addition to the summary in Table 3, a number of other abrasion control possibilities should be considered:

1. Sheet gauge of the culvert is normally selected for structural considerations. The normal commercial structural gauge range will usually also fit well for abrasion selections. Where highly abrasive or abusive sites are encountered, consideration can be given to increasing culvert metal thickness.

2. Attention to channel shape and culvert entrance design can reduce rock flow. If the velocity of approach can be reduced the water forces are lowered and the bed load is relaxed. Consider installing culvert inlet above channel invert grade to provide a



EXAMPLE SECTION  
1984 STUDY (84-R-5)  
(5X MAGNIFICATION)



EXAMPLE FACE  
1984 STUDY (84-R-5)  
(2.5X MAGNIFICATION)

FIGURE 11 Photomicrographs of abrasion rating D (sample section and face).

settlement basin that will fill with larger rocks and reduce the entrance velocity. In time the basin will fill level and still permit fines and smaller rocks to pass.

3. Install trash racks or rock guards upstream of abusive or severe abrasive sites to retain heavy short-term rock and debris flows before they reach the culvert inlet. This practice would, of course, require periodic removal of accumulations.

4. Multiple culverts and arch-shape culverts widen the approach channel considerably, reducing approach velocity. Consider stepping the inlet elevations of multiple culverts to decrease possibilities of floating debris plugging.

5. Paving of inverts with softer materials such as bitumen, asphalt, or plastics is of limited value for use as abrasion control for culverts. Such coatings do not resist rock flow impacts for long periods. The filling of invert corrugations increases rock velocity and does not appear to alter rock flow patterns to improve resis-

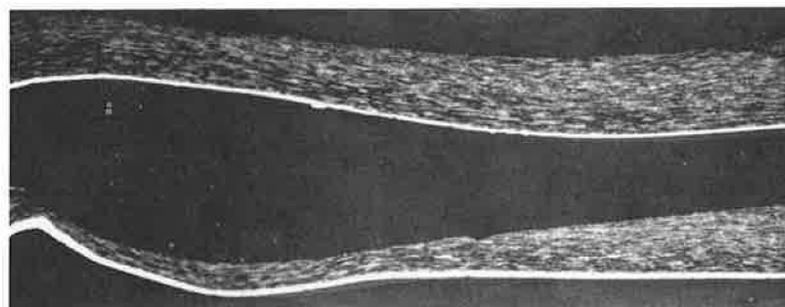
tance to abrasion (4, 5). Coatings can be beneficial for nonabrasive mixed-flow exposures such as sanitary sewer systems.

6. Structural plate shapes or other deep corrugations slow rock flows by causing a small reduction in average velocities and resulting rock energies.

7. Where difficult abrasive conditions cannot be avoided, permanent or expendable invert liners can be installed in the invert. Liners should run longitudinally and particular care is necessary to eliminate projections or joints in the rock flow bed. Invert liners of reinforced concrete, railroad rail, or structural steel have been used.

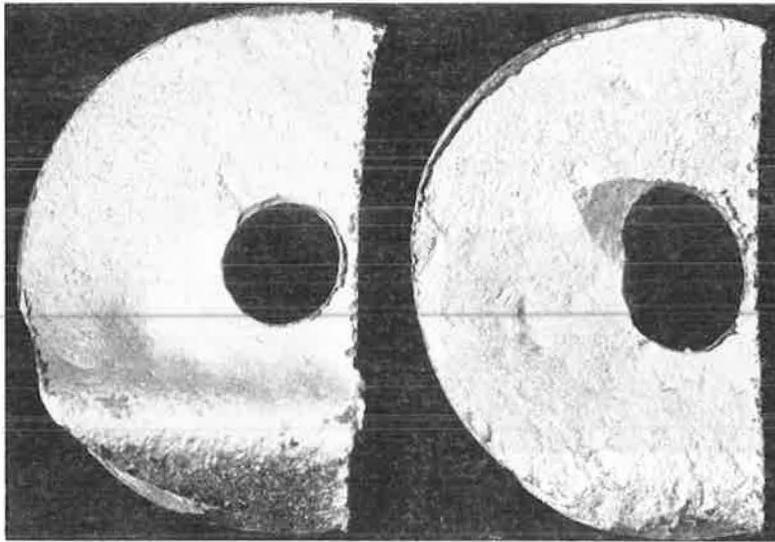
8. Flared or apron entrances do not improve abrasion resistance of a culvert. On the contrary, such entrances actually induct more rocks.

9. Reducing culvert slopes will reduce water flow velocities, rock flow energy levels, and thus abrasion.



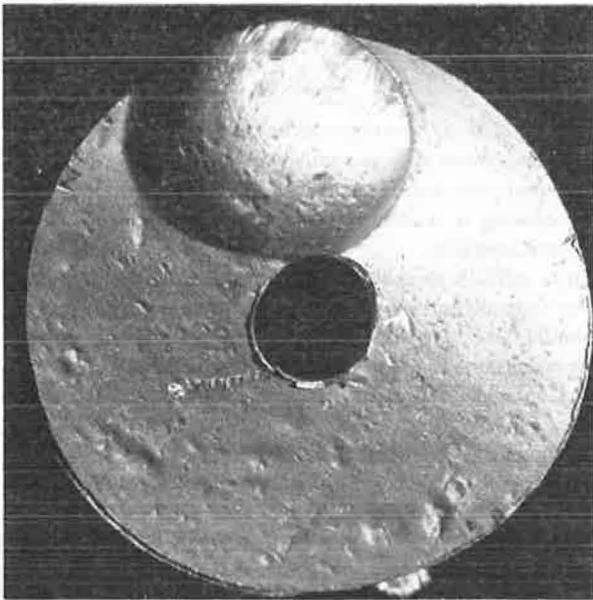
EXAMPLE SECTION  
1984 STUDY (84-004)  
(5X MAGNIFICATION)

FIGURE 12 Photomicrographs of abrasion rating E (sample section and face).



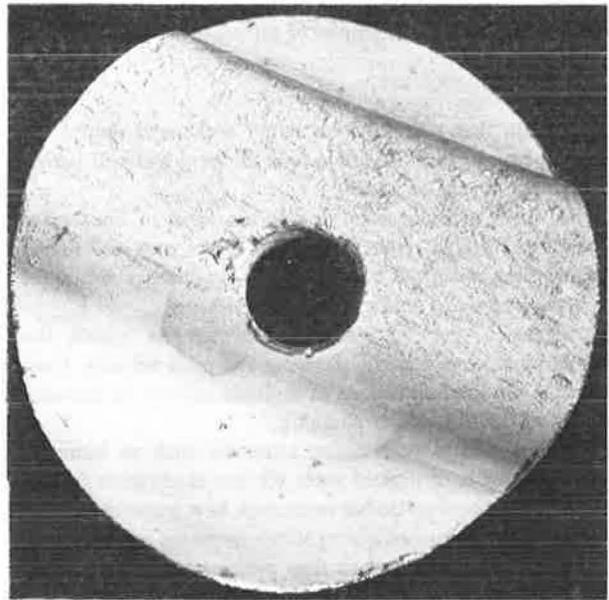
EXAMPLE FACE  
1984 STUDY (84-004)  
(2.5X MAGNIFICATION)

FIGURE 12 *continued.*

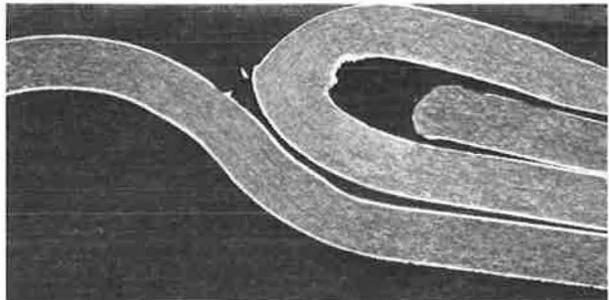


EXAMPLE FACE  
ALUMINUM ALLOY RIVET  
1984 STUDY (84-R-1)  
(2.5X MAGNIFICATION)

(2.5X MAGNIFICATION)



EXAMPLE FACE AND SECTION  
ROLLED, FORMED LOCK SEAM  
1984 STUDY (84-065)



(5X MAGNIFICATION)

FIGURE 13 Abrasion of joints and fasteners.

## ACKNOWLEDGMENTS

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# Corrugated Steel Plate Structures with Continuous Longitudinal Stiffeners: Live Load Research and Recommended Design Features for Short-Span Bridges

A. E. BACHER AND D. E. KIRKLAND

The deformation of longitudinally stiffened long-span corrugated steel culverts (beneath shallow overfills) due to live load, backfill, and overfill conditions is investigated. A culvert's structural configuration was monitored from installation through the introduction of live loads. The results of this research at Stenner Creek, and the P-13 proof test loading at Weir Canyon, have led to the conclusions that are recommended herein for incorporation in the design phase. Long-span corrugated metal structures that successfully incorporate these recommended design features are noted.

In 1963 the California Department of Transportation (Caltrans), in cooperation with the Federal Highway Administration, initiated a \$3.5 million culvert research program to assess structural behavior of culverts embedded in deep embankments. Included in this extensive culvert research program were three structural steel plate pipes: Chadd Creek, Apple Canyon, and DB Culvert, previously reported (1-6).

Caltrans has also completed a Category 2 (construction evaluated) research project of a super span design at Stenner Creek. Most recently, a proof test for P-13 loading was performed on a multiple super span at Weir Canyon.

Special features for long-span corrugated steel plate structures (with continuous longitudinal stiffeners) have been implemented

on subsequent Caltrans projects as a consequence of the Category 2 Caltrans culvert research project at Stenner Creek. Four permanent super spans and one permanent maxi span as well as two temporary super span corrugated steel plate bridges have been successfully installed in California. In addition, Caltrans has reviewed approximately 30 super span city and county installations.

## STENNER CREEK RESEARCH

Caltrans completed a Category 2 culvert research project at Stenner Creek, Bridge 49-146, in 1978, which included significant live load research findings (Figures 1 and 2). Live load design has been, and continues to be, a design consideration for minimum overfills on underground steel structures. The objective at Stenner Creek was to monitor (Figures 3 and 4) the shape changes due to backfilling and to live load in combination with incremental increases in overfill. It is apparent that live load can be a factor on a long-span culvert under shallow fill. The culvert is subject to flexing movement as the load passes over it.

## Peripheral Shape Changes

Each of the six transverse sections (Figure 5) had a designated point on either side and a point on top that corresponded to points