

The Mechanisms of Abrasion of Aluminum Alloy Culvert, Related Field Experiences, and a Method to Predict Culvert Performance

ALMONT H. KOEPF, Koepf and Lange Consulting Engineers, Orinda, California

•THE STRUCTURAL design (1, 2) and corrosion performance (3) of aluminum alloy culverts have been investigated and reported in a number of papers. There is also a need to investigate aluminum alloy culvert service in conditions of an abrasive nature to complete the basic studies. Several years of exposure of selected aluminum alloy culverts now provide data that may be used as a basis for substantiation of a mathematical hypothesis of abrasion performance. The purpose of this paper is to present an analytic approach to the behavior of aluminum alloy culvert under abrasive flow conditions as a prelude to methods of prediction of culvert performance.

BACKGROUND

Since the introduction of aluminum alloy culvert in 1961, the author has had the opportunity to personally observe the abrasion performance of well over 1,000 aluminum alloy culverts and a like number of galvanized steel culverts. These observations were further supplemented by observations by the author and other engineers of additional applications of aluminum.

Several preliminary conclusions were possible after reviewing the observations gathered. There was general uniformity of performance for similar terrains, bed load, and cumulative flow times. While there was some surface peening, there was no observed metal loss due to sand or very small rock bed loads, even when the flows were high. No significant evidence of corrosion was found on aluminum culverts in abrasive-type flow installations due to nearly neutral pH conditions. The abrasion rate was observed to be linear in nature.

Preliminary evaluation suggested that abrasion might be related to bed load flow energy, mass, and velocity, with contributions from the effect of the repetitious corrugations.

EROSION-CORROSION CYCLE

The mechanics of wastage of aluminum alloy culverts under abrasive flow conditions needs to be reviewed. This is particularly important because the total cycle causing metal loss of aluminum due to erosion-corrosion has been observed by the author to differ markedly from the cycle causing metal loss from galvanized steel culvert.

Galvanized steel exposed to an abrasive flow follows an erosion-corrosion-erosion cycle. The abrasive material removes the relatively soft zinc and exposes the steel surface below at a rate that depends on the severity of flow; iron oxide is then formed, only to be removed by further abrasive flow. This mechanism of corrosion-erosion attack causes steady rates of wastage of steel culvert inverts. The surface hardness of steel was observed to resist the abusive action of larger rocks under severe conditions of flow moderately well. The wastage rate appears to be governed more by the corrosion portion of the erosion-corrosion couple than by abrasion only. The progressive erosion-corrosion cycle proceeds in all types of abrasive flow including sand and

gravel. In cases where water may be corrosive, wastage would increase. A generalized cumulative erosion-corrosion curve is shown in Figure 1 to illustrate the characteristic metal wastage patterns of steel culvert.

The corrosion resistance of aluminum alloys eliminates the type of corrosion attack pattern that produces and continues rust on steel. The cumulative curve of erosion-corrosion across the full range of flows as developed for aluminum alloys may be simulated on Figure 1. When superimposed the divergent performance of steel and aluminum becomes clear, even though they appear to ultimately perform comparably over extended periods.

MECHANICS OF ABRASION

Nomenclature

- P = Pressure force of water, lb
 W = Weight of rock, lb
 F = Friction resistance, lb
 N = Normal force on surface, lb
 I = Mass moment of inertia of rock, ft lb sec²
 u = Rock velocity, ft/sec
 V_w = Mean pipe velocity, water ft/sec
 V_e = Culvert water entrance velocity, Q/A , ft/sec
 β = Incline slope of culvert, 27 deg for $2\frac{2}{3} \times \frac{1}{2}$ shape
 ϕ = Slope of culvert
 $\theta = \beta - \phi$
 ρ = Density of rock in water, lb/ft³
 r = Spherical radius of equivalent rock, ft
 a_L = Linear acceleration of rock, ft/sec²
 a_R = Rotational acceleration
 a = Total acceleration, ft/sec²
 s = Distance of free flow, ft
 e = Impact velocity restoration factor
 μ = Friction coefficient
 ΔKE = Mean impact kinetic energy, ft lb
 KE_u = Peak kinetic energy, ft lb
 x = Horizontal distance, ft
 y = Vertical distance, ft

Mathematical Hypothesis

The source of surface abrasion on the invert of metal culvert is the cumulative result of impact or rubbing action by particles of hardness equal to or greater than the metal surface. To describe rates and predict abrasion in its varying parameters satisfactorily it is desirable that abrasion action be reduced to a mathematical hypothesis. Observations showed that culverts subjected to active flow are self-scrubbing (i.e., self-cleaning) including corrugation valleys. Observations also have consistently shown no evidence of abrasive action by sand or very small rocks, while flows containing

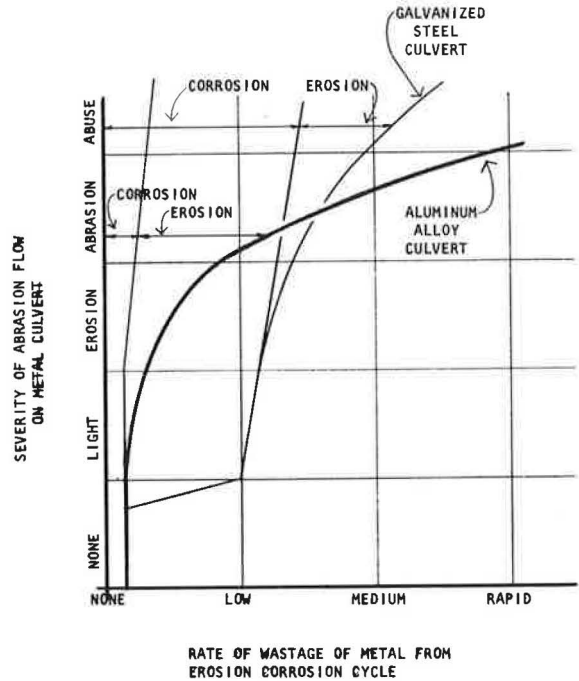


Figure 1. Cumulative curve of erosion-corrosion.

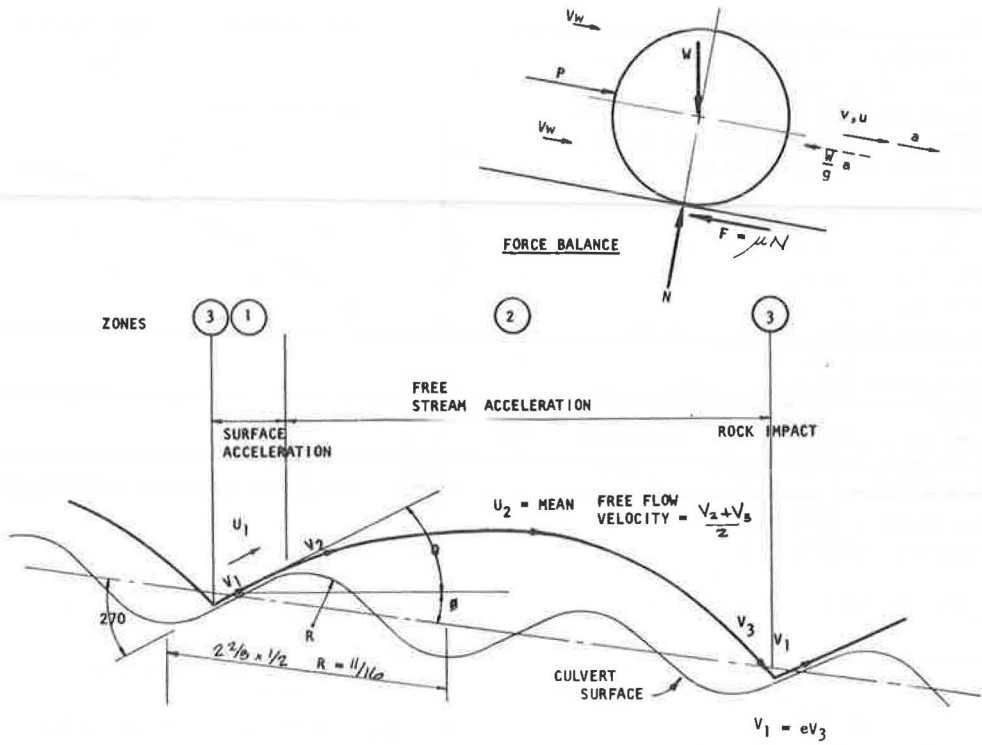


Figure 2. Rock cycle path.

increasing quantities and sizes of rock show increasing surface abrasion. From this, abrasion may be related to the cumulative kinetic energy of the rocks that flow through, i.e., to mass and velocity.

The energy theory permits the use of conventional force, velocity, and acceleration equations as a framework for analysis (4). Figure 2 shows the forces acting on a single rock, represented by a sphere. When the driving force, water pressure, exceeds the net resistance of gravity and friction the rock will move and continue to accelerate to a terminal velocity, u . Since culvert inverts are not smooth but corrugated, the actual path of a rock (particularly a smaller rock) does not follow a constant path but rather a series of cycles as shown in Figure 2 (5). Observation indicated that the rocks move by translation. During the initial portion of a flow cycle the rock is accelerated up the corrugation incline, proceeds by free flow over one or several corrugations, then drops to impact on the incline, which reduces the velocity and starts the repeat of the cycle.

Using basic equations of kinetic and potential energy and the flow path of Figure 2, the analysis may be developed for each zone as follows:

Zone 1—Surface flow

$$a_L = 0.075 \frac{(V_w - u_1)^2}{r} - 32.2 (\sin \theta + \mu \cos \theta) \quad (1)$$

Zone 2—Linear flow

$$a_2 = 0.075 \frac{(V_w - u_2)^2}{r} - 32.2 \sin \theta_{\text{mean}} \quad (2)$$

$$\approx 0.075 \frac{(V_w - u_2)^2}{r} - 32.2 \tan \phi \quad (3)$$

$$S_2 = \frac{2u_2^2}{g} \tan \beta \quad (4)$$

$$V_3 - V_2 = \frac{2u_2}{g} \tan \beta \left(0.075 \frac{(V_w - u_2)^2}{r} - 32.2 \tan \phi \right) \quad (5)$$

Zone 3

$$V_1 = eV_3 \quad (6)$$

Equations 1 through 6 are derived from the basic equations of dynamics (4).

$$\Sigma F = \frac{W}{g} a \quad \text{Force balance} \quad (7)$$

$$F = \mu n \quad \text{Friction} \quad (8)$$

$$V = eV_0 \quad \text{Impact restoration} \quad (9)$$

The solution includes a number of assumptions. For example, a rock is considered a sphere of uniform density, rotation is assumed minimal, culvert corrugations are $2^{2/3}$ by $1/2$ in. and the free flow velocity, u_2 , is taken as the arithmetic mean between start and impact. Such a method is considered reasonable in dimensional analysis provided the forms of the equations are substantiated by experimental data. Further, Zone 1 has little effect on the overall solution and since it is of the same form as zone 2 it may readily be combined with Zone 2 to eliminate one set of equations.

Two alternate solution forms to the foregoing equations are possible. The first solution is based on calculations using actual flow paths to determine velocities, accelerations, and distances. It solves for the magnitude of the velocity reduction at impact $(1 - e)$, and hence a measure of the energy lost on each impact ΔKE . The second solution is based on solving for a constant or mean rock flow velocity, u , and an equivalent friction factor, μ , resulting in peak energy available for any impact KE_u . It is recognized that rock flow in culverts is at best an inexact science and reproducibility of results depends on similarity of a host of variables such as rock size, shape, frequency, hardness, site geometry, mean flow patterns, short-term higher flow rates, and rock availability. To account for and minimize these variables a field test program was undertaken to study the apparent effect of these variables on the dimensional analysis or mathematical hypothesis. The overall effect on aluminum alloy was also cataloged so that the calculated performance energy levels could be rated against field performance.

Rock Size, Shape, Availability, and Hardness

A basic assumption in the analysis was that progressive abrasion will follow a generally linear pattern. This has been confirmed to date by several investigations of the selected culverts over a period of years. If anything, abrasion rates in average installations appear to diminish somewhat.

The field investigation program also confirmed that the incidence of abrasion varies somewhat due principally to differences in terrain and rainfall patterns. It is interesting to note, however, that ranges observed as a result of the variations were not excessive. For example:

1. Areas with considerable ground cover will restrict rock flow and thus cause less abrasion. Increased abrasion will occur in areas with little ground cover and loose rock in the slopes. A steep, bare, loose rock slope subjected to sudden and repeated heavy flows would represent the most severe exposure possible for culvert abrasion.

These appear to be more likely to occur on the west slopes of the North Pacific Coast. Because of these conditions a substantial number of the sites used for study are concentrated in the Pacific Northwest.

2. Where few rocks are present, such as in the central United States, abrasion of aluminum alloys is not expected and was not observed.

3. Sharp, hard rocks cause more relative abrasion than less angular, rounded glacial or soft rock when all other conditions are equal.

Velocity

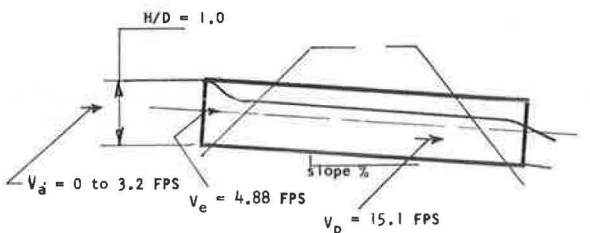
The analysis is particularly dependent on the velocity of the rock, since any velocity developed is a squared term. Consequently, it is necessary to review the different velocities that may occur in a typical culvert installation (6):

1. Approach velocity, V_a , is the velocity in the approach channel. This velocity is low, usually less than 5 ft per sec, and provides limited information to the designer on expected performance. It furnishes no insight into rock flow.

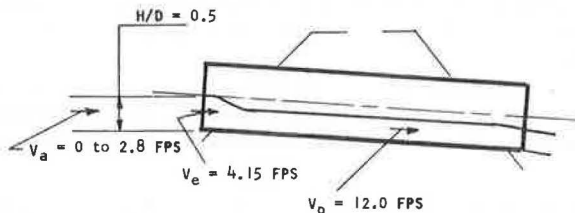
2. Entrance velocity, V_e , is the velocity at the entrance to a culvert. Designers frequently use the entrance flow as a guide to selection of culvert size. Typically, the 10-year flood flow, Q_{10} , with a fully submerged entrance is used as a basis of design. Such velocities are a direct function of culvert diameter and entrance geometry. Designers frequently attempt to define abrasion with a limit on entrance velocity, as in the Bureau of Public Roads publication, "Corrugated Metal Pipe Culverts" (7), which suggests a value of 5 ft per sec. Although the flood flow method appears reasonable for culvert sizing, it has very limited effectiveness as a method of defining abrasion. Since V_e is directly proportional to culvert diameter, an entrance velocity of 5 ft per sec merely indicates that a 42-in. maximum size culvert had been selected. On the other hand, entrance velocity can serve as a guide to describe probability of number and size of rocks that may be inducted into the culvert. Field observations of rock flow indicate that a Q_{10} flooded entrance velocity, V_e , of less than 4 ft per sec will not induct a significant number of 2-in. and larger rocks, and where V_e exceeds 5 ft per sec, it must be combined with frequent induction of rocks over 3 in. in size before significant abrasion can be expected.

3. Pipe velocity, V_p , is the velocity of the water in the culvert once clear of the entrance. It is a function of flow (Q_{10} for example), culvert diameter, culvert slope, and corrugation shape. As an example, a 42-in. culvert with a Q_{10} of 47 cu ft per sec at the flooded entrance will develop a pipe velocity of 11 ft per sec on 5 percent slope or 22 ft per sec on 30 percent slope. Pipe velocity describes the degree of abrasion from velocity when combined with rock flow. However, the use of V_p as the sole basis of degree for abrasion is not recommended because by definition it occurs only once in 10 years and poses an unrealistic level.

4. Mean pipe velocity, V_w , is a defined velocity in the culvert as a result of flow through



3A Conditions at Submerged Entrance, Typical $Q_{10} = 47$ CFS



3B Conditions at Half Submerged Entrance, Typical $Q = 20$ CFS

Figure 3. Velocities experienced in typical culvert having 42-in. diameter, projecting entrance, 10 percent slope.

a projecting entrance filled half the depth of the culvert, selected to represent a reasonable combination of frequency of occurrence and velocity magnitude. Mean pipe velocity is used for this analysis.

5. Rock velocity, u , is the net velocity of a rock as it passes through the culvert when subjected to a forcing flow due to V_W . The rock velocity may vary from zero to V_W and will of course vary between impacts.

An example of the several velocities that may be experienced in a typical culvert are shown in Figure 3 (8). For the analysis a 42-in. diameter, projecting entrance, 10 percent slope culvert is shown.

Mean Impact Energy

The mean energy loss to the surface at each impact of a single rock (4) as it passes through the culvert is shown as

$$\Delta KE = \frac{W}{2g} V_W^2 (1 - e)^2 \quad (10)$$

When the rock is considered as an equivalent sphere, then

$$\Delta KE = 5.21 r^3 V_W^2 (1 - e)^2 \quad (11)$$

The total energy to which a surface may be subjected over a long period of time is proportional to these energy equations.

This solution requires analysis of the rock flow cycle (Fig. 2). A series of rock flow tests were run in culverts. From these tests calculation curves of both the velocity impact factor $(1 - e)$ and the energy impact factors $(1 - e)^2$ were prepared as shown in Figure 4.

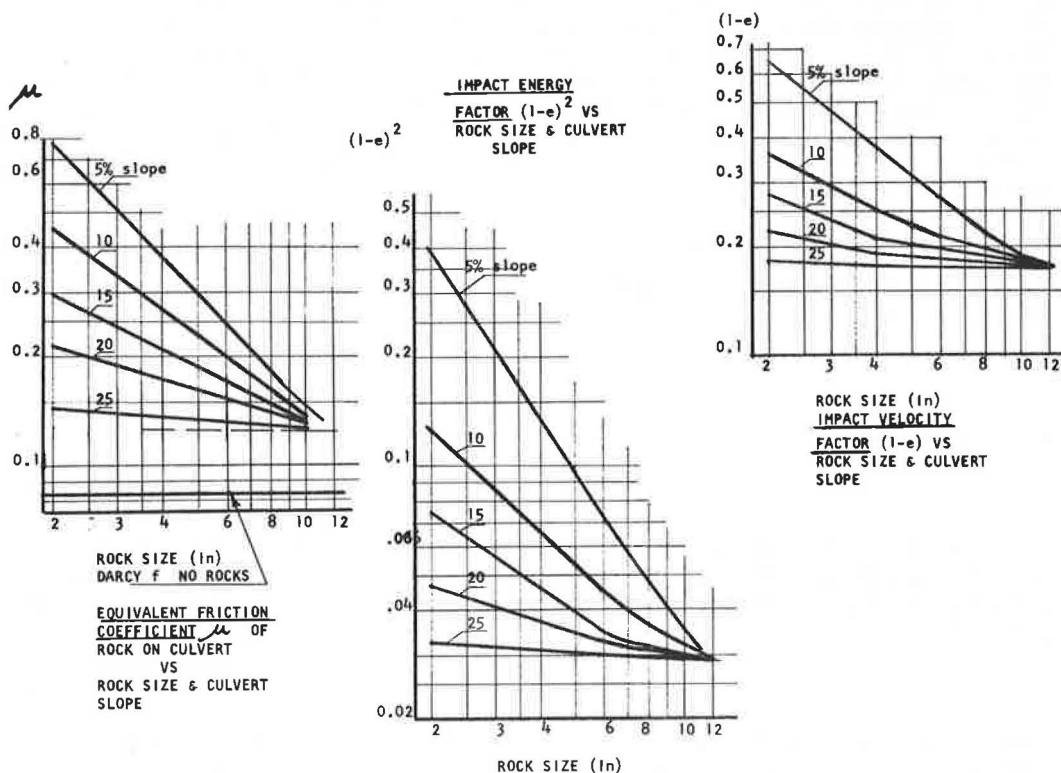


Figure 4. Curves of friction and energy factors—aluminum alloy culvert.

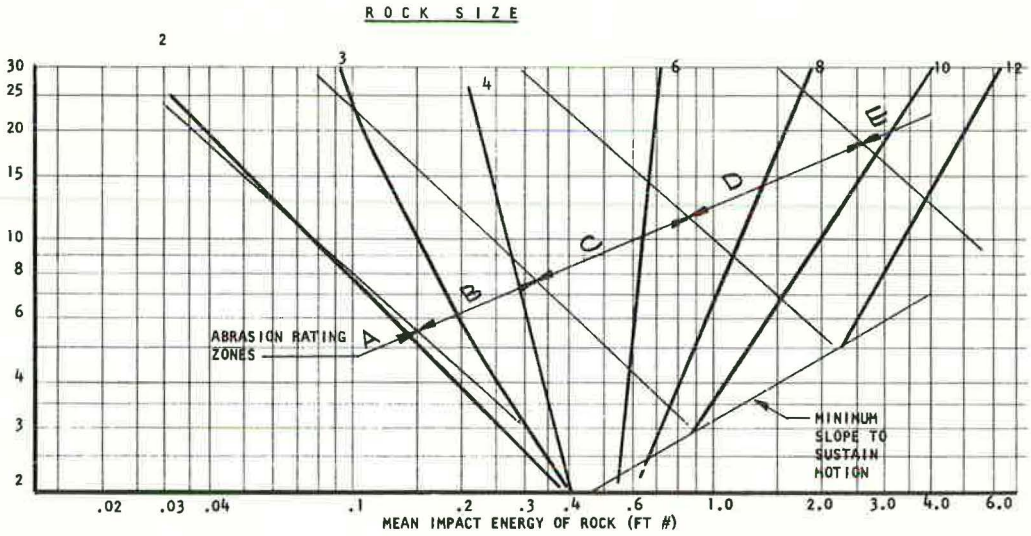


Figure 5. Typical mean impact energy curves for 48-in. culvert.

The magnitude of the water flow in the pipe at the precise time the mathematical rock passes through is certainly highly variable. A substantial minimum flow must exist to permit rocks to move at all. Combining the mean energy loss in Eq. 10 or 11 and Figure 4, a mean impact energy curve may be calculated for a representative range of slopes, rock sizes, and culvert sizes. Figure 5 shows a typical set of curves for a given culvert size. The lower cutoff line approximates the minimum flow and slope conditions necessary to commence rock movement. It is interesting to note that impact energy actually increases for small rocks as the culvert slopes are reduced, due to drastic increases in $(1 - e)$ resulting from the steeper impact angles with the inclined corrugated surface. As the rocks become larger they tend to pass across the corrugations, causing the energy line to increase with increased slopes.

Figure 5 includes a series of abrasion rating lines developed from field observations that are discussed later.

Peak Available Impact Energy

An alternate approach to analysis comes from the peak available impact energy method (4) where

$$KE_u = \frac{W}{2g} u^2 \quad (12)$$

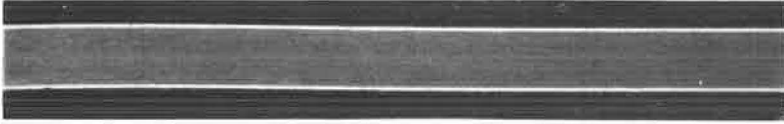
When the rock is considered as an equivalent sphere, then

$$KE_u = 5.21 r^3 u^2 \quad (13)$$

This represents the peak energy available in a rock that becomes suddenly arrested while in the stream. This method of analysis becomes more indicative of energy levels that may cause occasional gouging. The peak energy requires determination of relative rock velocity, u , from

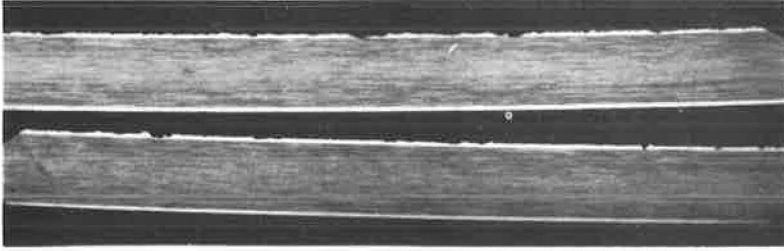
$$(V_w - u)^2 = 430 r (\mu_m - \sin \phi) \quad (14)$$

This equation uses an equivalent constant flow (acceleration zero) and an equivalent friction coefficient, μ_m , which takes into account rock size and culvert slope. It is derived from the flow equations of the previous section.



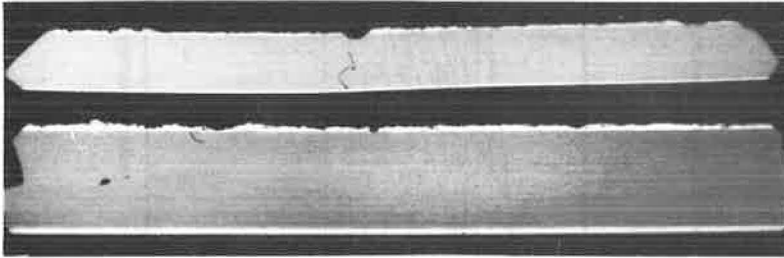
ABRASION RATING A

67-330



ABRASION RATING A/B

67-354



ABRASION RATING B

67-335



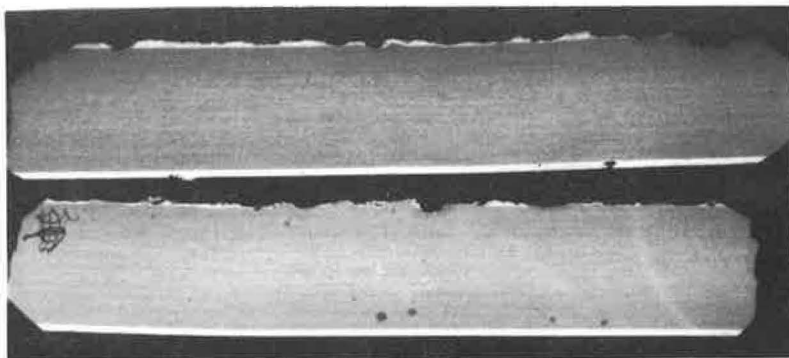
ABRASION RATING B/C

67-316

Figure 7. Photomicrographs of culvert sections.

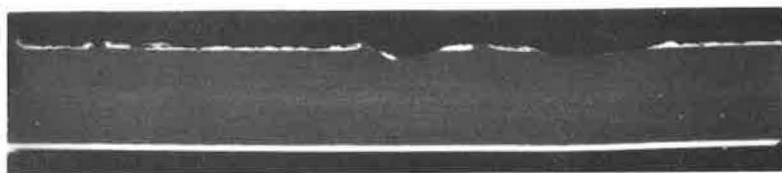
over many years. This approximation is very necessary to the rating and it proved to be manageable with some experience.

Culverts were also sampled by drilling out coupons from the invert crowns and subjecting them to laboratory examination. Detailed surface and cross section inspection was conducted on each culvert to confirm the visual rating. The coupon samples were selected to be representative of the more severe portions of the culverts given a visual abrasion rating. Abrasion occurs on the upstream portion of the crown radius of the corrugations at the invert line. Figure 7 shows selected photomicrographs representing examples of no effect (Rate A), non-erosion (Rate B), erosion (Rate C), and abrasion (Rate D). The sample of no effect is included to show clearly the extent of the



ABRASION RATING C

67-326 - 7



ABRASION RATING D

67-319

Figure 7. (continued).

cladding on the surface—5 percent of the thickness or approximately 0.003 in. The non-erosion (Rate B) sample shows characteristic light surface pebbling but no significant removal of cladding. The cladding is slightly softer than the core so will show surface effects more readily than the core. The sample of erosion (Rate C) shows the same pebbling texture and light random gouging but to a degree sufficient to visibly disturb and gradually remove metal. The abrasion sample (Rate D) represents the cumulative result of pebbling and gouging that more rapidly reduces the metal thickness by removal. The abusive condition (Rate E) is not shown as no instances were observed in this sampling. Such a sample would show more rapid progressive removal by gouging and pounding than shown in example D. Rivet projections are particularly vulnerable in abusive flow and are rapidly worn flush when they project on the crown of the invert. All samples in Figure 7 represent the typical result of 5 years of exposure.

Each coupon was subjected to careful surface and cross section examination, and from these examinations the depth of metal removed was recorded. Dividing this depth by the years of exposure provided an average wastage abrasion rate expressed in inches per year (IPY). The metal culvert gage was then divided by the abrasion rate (IPY) to produce analytical service life estimates in years. This method proved to be a good comparison check on the visual rating system. Reinforced by the laboratory IPY values, the visual abrasion rating and the energy rating performance data could be handled

TABLE 1
ABRASION PERFORMANCE RATING SCHEDULE

Performance Zone Ratings	Effect on Surface of Crown of Corrugation, Invert Only ^a
A	<u>No surface effect.</u> No reduction in service life due to bed load abrasion. Abrasion design prediction life 50 years minimum.
B	<u>Non-erosive.</u> Some slight roughening of the metal surface but no metal removal by erosion action. No reduction in normal service life of aluminum culvert. Abrasion design prediction life 50 years.
C	<u>Erosion.</u> Surface roughening and slight progressive removal of metal from culvert. Estimated maximum average rate on invert crown 0.002 in. per year. Some gouging may be noted if rocks tend to be large. Abrasion design prediction life 25 to 50 years depending on gage of metal.
D	<u>Abrasion.</u> Surface roughening and slow removal of metal from culvert. Estimated maximum average rate on invert crown 0.002 to 0.005 in. per year. Definite reduction in pipe life due to abrasion. Gouging of surface may be expected. Design prediction life 15 to 25 years or more depending on gage of metal.
E	<u>Abusive.</u> Surface roughening and rapid removal of metal from culvert. Estimated maximum average rate on culvert crown greater than 0.005 in. per year. Definite reduction in pipe life. Design prediction life under 25 years depending on gage of metal.

^aAbrasion affects only this portion of the surface.

TABLE 2
COMPARISON TABLE OF ABRASION RATINGS

Estimated Service Life (years)	Peak Energy (ft lb)	Abrasion Rating Recommended	Wastage of Metal (increase per year)
50+	0.1 and less	A	Nil
50	0.1 to 1.0	B	Nil
25 to 50	1.0 to 10	C	0.002
25+	10 to 100	D	0.002 to 0.005
Under 25	100 and higher	E	0.005

TABLE 3
ROCK SIZES AND CULVERT SLOPE

Abrasion Rating Desired	Rock Size ^a (in.)	Maximum Slopes (percent) for Typical Culvert Sizes		
		24 in.	48 in.	72 in.
A	2	— any slope —		
B	3	25	20	7
	4	12	9	4
	6	6	4	2
C	6	45	14	8
	8	25	9	6
	12	—	5	4
D	8	—	25	18
	12	—	13	10

^aStatistical peak rock size expected.

with assurance. Having the results, the procedure could then be reversed and be used as a method of prediction of performance on new culverts.

ESTIMATING SERVICE LIFE USING ENERGY CURVES

The knowledge developed and shown in Figures 5 and 6 and the abrasion rating system may be rewritten in the form of a service life chart, Table 2. For convenience the peak energy curve (Fig. 6) is used. A spread in expected service life may be expected when wastage rates are applied, due in large part to the wide differences in metal thickness (from 16 to 8 gage) that are commonly used.

With these recommendations an experienced engineer can predict performance by evaluating the channel to be drained in the immediate proximity to the upstream entrance to a culvert and estimating what maximum rock size can be expected to reach and pass repeatedly through the culvert. He must consider slopes, soil types, and rainfall patterns. Table 3 is included as a guide.

In addition to the size-slope table a number of other possibilities should be considered:

1. Gage of the culvert is normally selected by structural considerations, and the thickness of the metal selected must be combined with the abrasion rates (IPY) to give an accurate picture of anticipated service life.
2. Channel and culvert entrance design is the key to reducing rock flow. This factor is the most important to design because rock size limitation is highly desirable. Reduce the velocity of approach, V_a , wherever possible.
3. Paving of inverts with softer materials such as bitumen or asphalt is ineffective for use as abrasion control. Such coatings cannot resist rock flows and the filling of invert corrugations does not appear to improve resistance to abrasion.
4. Structural plate or deep corrugations will slow rock flows, causing a reduction in rock energies.
5. Where difficult abrasive conditions cannot be avoided, invert gages should be increased and/or liners installed in the invert.
6. The use of oversize culverts will reduce pipe velocities considerably and thus reduce abrasion energies.
7. Flared or apron entrances do not beneficially improve abrasion resistance.

FUTURE

The intent of this paper is to stimulate consideration of the abrasion of aluminum alloy culvert as being within a mathematical system framework supported by field investigations.

It is expected that the program of field observations will continue to improve the accuracy and basis of performance predictions and development of design parameters.

ACKNOWLEDGMENT

The author wishes to express appreciation of the support provided by the Aluminum Association in preparation of the material.

REFERENCES

1. Koepf, A. H. Review of Structural Design Methods for Aluminum Alloy Corrugated Culverts. Highway Research Record 176, p. 43-56, 1967.
2. Koepf, A. H. Structural Considerations and Development of Aluminum Alloy Culvert. HRB Bull. 361, p. 25-71, 1962.
3. Lowe, T. A., and Koepf, A. H. Corrosion Performance of Aluminum Culvert. Highway Research Record 56, p. 98-115, 1964.
4. Singer, F. L. Engineering Mechanics. Harper and Bros., New York, 1943.
5. Rouse, H. Fluid Mechanics for Hydraulic Engineers. McGraw-Hill, New York, 1938.
6. U.S. Bureau of Public Roads. Design Charts for Open-Channel Flow. Hydraulic Design Series No. 3., U.S. Govt. Printing Office, Washington, 1961.
7. U.S. Bureau of Public Roads. Corrugated Metal Pipe Culverts. U.S. Govt. Printing Office, Washington, 1966.
8. U.S. Bureau of Public Roads. Hydraulic Charts for the Selection of Highway Culverts. Hydraulic Engineering Circular No. 5, U.S. Govt. Printing Office, Washington, 1961.