Procedures for Determining the Most Economical Design for Bridges and Roadways Crossing Flood Plains

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Highways crossing the flood plains of major streams are combinations of bridges and approach embankments. The decision as to which portion of the total roadway length shall be on bridge and which on fill involves engineering economy as well as bridge design. Bridges cost more per unit length than approach fills so that, within reasonable limits, the combination of short bridge and long approach has lower first costs. On the other hand, this combination restricts the channel and during floods raises the water level upstream, which may cause damage from flooding. A second and interrelated decision concerns the roadway elevation of the approach fill. Lower fills are overtopped by smaller floods, with damage to the fill and interruption of traffic during and after a flood. On the other hand, overtopping lowers the upstream water level, thereby reducing upstream flood damage.

This paper presents a procedure for determining the most economical combination of bridge and embankment lengths and approach roadway elevation. The analysis takes account of the following costs: capital recovery on the initial investment, maintenance, embankment flood damage, traffic delay and detours, and backwater damage. Two separate examples are presented considering streams in flood plains 900 and 5,000 ft wide.

● FUNDS for highway improvement are limited and highway needs are great. Because a sizeable percentage of highway expenditures is for major drainage structures, economy in their design is highly desirable. In the case of bridges crossing streams having broad flood plains, the first decision probably is to determine how long the bridge is to be and at what height to place the approach embankments if they are to serve as overflow spillways during major floods. This paper proposes a method for determining the most economical combination of bridge and approach embankments for this situation.

To demonstrate the proposed method, two typical examples are worked. The procedure is as follows:

1. Based on an analysis of crossing conditions at the site in question, several bridges ranging from short to long are laid out and priced. The elevation of these structures is set sufficiently high to clear any anticipated flood.
2. Approach fills built to several heights are fitted to each of these bridges and their costs determined. It is anticipated that under extreme flows all but the highest of these approach fills will be overtopped.
3. By an analysis involving the predicted flood flows on the stream, the characteristics of the site, the length of the bridge, and the height of the approach embankment, stream water surface elevations are determined for the several conditions.
4. For each length of bridge, the most economical approach embankment height is determined. Factors taken into account include the capital costs of embankment and pavement, the statistically predicted annual costs of anticipated flood damage to the

particular site would, if possible, be based on past stream flow records. For more information on frequency curves see Linsley et al (4, pp. 555-559).

Number of days and times a given flow has been exceeded.—This information is given in two graphs; one, the number of days that a given flow is exceeded, and the other, the number of times various flows have been exceeded (see Figs. 7 and 8). On large streams, this information may be available from past records.

Stage-discharge curve.—The stage discharge relationship is shown in Figure 9. The values for plotting this curve may be computed for any site by using conveyance and river slope described by Bradley (1). Normal stage represents the elevation of the water surface at the bridge site when the channel is unrestricted by any crossing at all.

Stage-damage curve.—The stage-damage curve is a plot of expected damage to improvements lying in or adjacent to the flood plain for a given stage (see Fig. 10). This must be constructed for each individual bridge site, recognizing future changes in flood plain use. In constructing the damage curve for the example problems, it has been assumed that damage is linear with stage to simplify the computations. Some of the U.S. Geological Survey water-supply papers give information on various flood magnitudes and damages. Also, the U.S. Army Corps of Engineers has made numerous studies on this subject. As yet, however, authoritative procedures for estimating flood damages are still lacking.

Stage-damage relationships are, of course, dependent on bridge site location. Damages in unsettled areas would be extremely low; they would increase with the intensity of land use. Again, stage-damage relationships would vary depending on encroachment of developments into the flood plain and the presence of dikes or levees that might be overtopped.

Traffic detour costs.—The traffic detour cost is the added cost to vehicle owners who detour by way of another stream crossing or who defer an intended trip. A detailed presentation on detour driving costs is outside the scope of this paper. As is the case with flood damage costs, basic data and procedures for making such computations have not yet been fully agreed on. Their magnitude will, of course, be dependent on such factors as the number of cars, the added distances traveled in using the detour, detour road configuration, expected speeds, and appropriate charges for added commercial and noncommercial time.

Methods and cost data for reasonably approximating the cost of detouring by another crossing are found in Woods (5). On the other hand, economic measures of the cost of postponed travel are lacking.

Costs of damage to embankment from flood overflow detour time during damage repair.—In the example problems, embankment damage is assumed to be proportional to the stage above the embankment roadway. The time for damage repair is assumed to be proportional to the embankment damage. These approximations were made because very limited information was available on how these damages might be evaluated. (It is assumed that the bridge proper is designed to withstand a flood of any magnitude without damage.)

Maintenance costs for bridge and embankment.—This information should come from cost records of the highway agency. It is to be expected that bridge maintenance costs will vary with the type of bridge, climate, and region; embankment maintenance costs (exclusive of flood repairs) will be a function of rainfall and other happenings that bring erosion and parallel deterioration. In this study, these maintenance items have been charged as an annual cost per lineal foot of bridge or embankment.

SELECTING LEAST COSTLY COMBINATION

In this study, cost comparisons are made between bridges of several selected lengths. In turn the bridge of each length has several alternative approach embankments of different heights. The first step in the analysis is to determine, for each bridge length, the least costly embankment height. Then the total costs of bridges of different lengths are compared, each with its most favorable embankment arrangement. The tables accompanying the report show in detail how the various costs are computed. In an actual cost study some of the columns and tables can be combined to simplify the computations.

embankment, traffic detours or delays during and after flooding, and backward damage to upstream property.

5. The total annual cost of bridge, approaches, and anticipated flood damage and traffic detours or delays for each bridge length is determined by combining the capital and maintenance costs of the bridge with those associated with the embankment. The bridge length of lowest total cost is the most desirable from an economic point of view.

In certain instances irreducibles may assume such importance that economy alone should not govern the final decision. For example, it could be undesirable to have a strategic bridge on a major route completely out of service for even a short time. On the other hand, the possibility of a short loss of use should not be controlling in the design of a stream crossing for a secondary road carrying little traffic. Even where such irreducibles might appear important, however, an economy study provides a dollar measure against which such irreducibles can be weighed, thus narrowing the area of uncertainty and providing a valuable tool for decision making.

Some of the costs employed in this paper are not based on actual situations. Rather, seemingly reasonable values have been taken from a variety of sources or, in some cases, assumed without detailed explanation. This was purposely done in order not to obscure the main reason for the paper, which is to develop a procedure for the analysis. It is anticipated that the analyst following this procedure in a real-life situation will develop his own cost information from a study of the site coupled with data supplied by the various divisions of his highway agency.

Another criticism of the proposed method concerns the considerable amount of data collecting and computation required to carry out the procedure as outlined. For many years design engineers have been attempting to weigh the factors included in this analysis. Often this weighing could only be done in a qualitative way because data and procedures were lacking. What is now proposed is that these factors be quantified and converted to money terms to provide a more reliable appraisal of each situation. Investments in major structures are large; it would seem logical to apply an added increment of time and effort to prove that the design makes solid economic sense.

DESCRIPTION ON EXAMPLE PROBLEMS

Problem 1

A two-lane bridge with approach embankment is proposed for crossing a river and wide flood plain. Five alternative bridge lengths are to be compared; these are 800, 1,100, 1,500, 2,000, and 2,500 ft. With each bridge, approach embankments have been set at several levels. Bridges less than 800 ft in length were not considered because they would encroach on the natural channel of the stream (see Fig. 1).

Background information and graphs necessary for the economy study are found in Figures 1 through 13. Tables 1 through 5 outline the method of computation, Table 6 shows the resulting costs. A detailed description of the procedure is included in the text of this report.

Problem 2

This example shows the results of an economy study for a shorter bridge. Lengths considered are 100, 150, 200, and 300 ft. It was chosen because the lengths fall within the range of field verification for the backwater method employed in the analysis.

The proposed bridge and embankment are to carry a two-lane road across a river and flood plain whose cross-section at the bridge site is shown in Figure 14. Table 7 summarizes the results of the analysis; Figures 15 through 20 supply a portion of the necessary data. The remainder comes from source documents.

DATA SOURCES FOR EXAMPLES

For an actual situation, much of the hydraulic and cost information for an economy study is developed as a part of the conventional design process; the remainder can be obtained with a reasonable amount of additional effort. For this paper, however, the

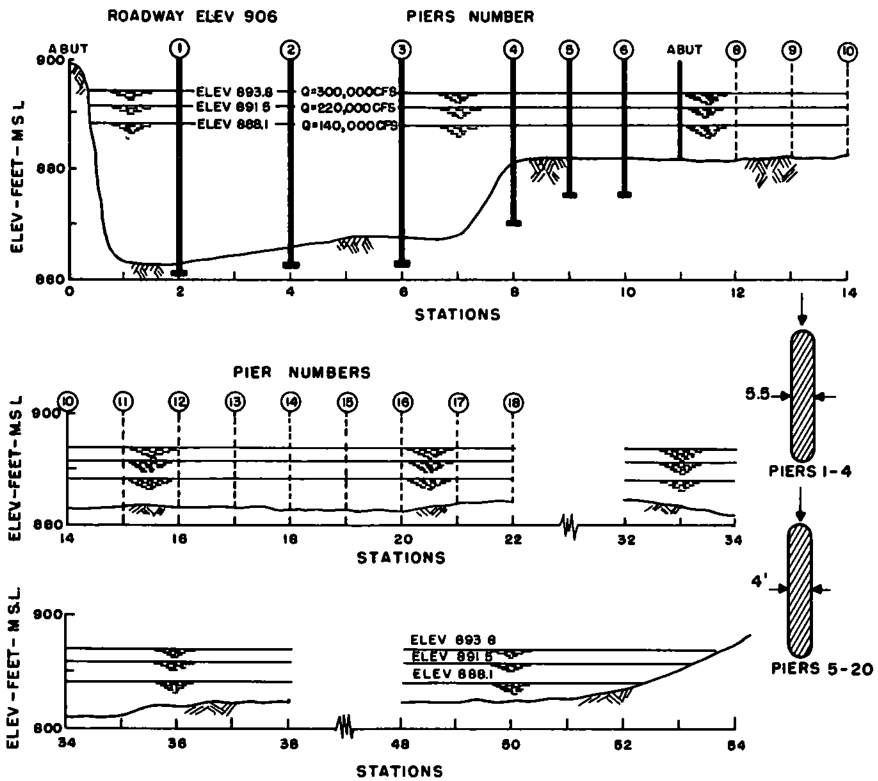

Figure 1. Section of river at bridge facing upstream, example 1 (long bridge) (courtesy of J.N. Bradley).

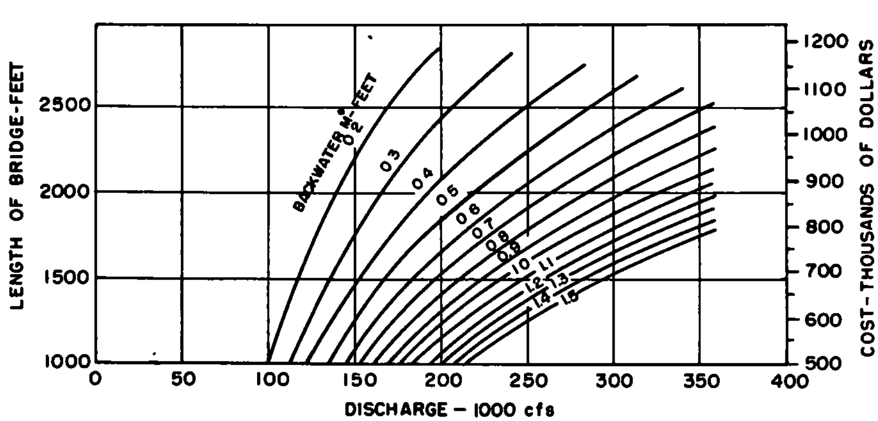

Figure 2. Bridge backwater (courtesy of J.N. Bradley).

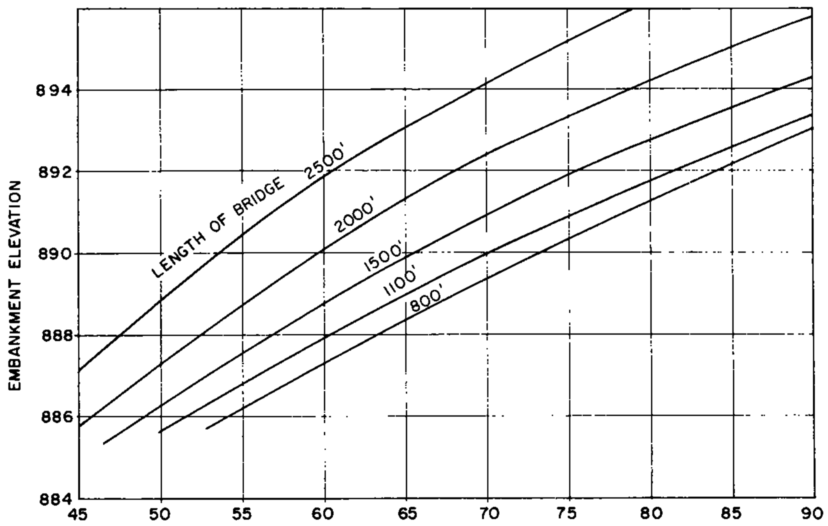

Figure 3. Total cost of embankment and paving (courtesy of J.N. Bradley).

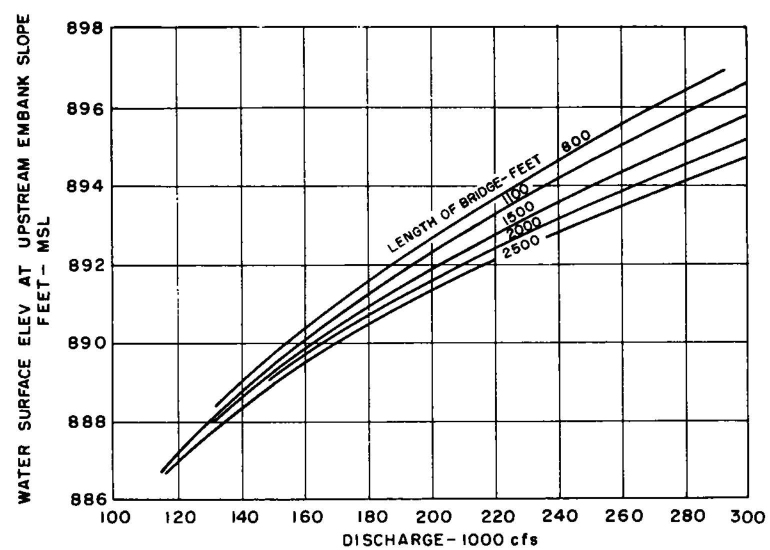

Figure 4. Water surface elevation at upstream embankment slope (courtesy of J. N. Bradley).

In an economy study such as this, cost comparisons should be between alternative bridge-roadway combinations of equal lengths. In cases where, because of differences in approach embankment height, the bridge plus embankment lengths differ among alternatives, pavement lengths have been increased for the shorter alternatives to give each the same over-all length. Again, an economy study is concerned with differences between alternatives. It is differences in costs that are relevant. This means that costs common to all alternatives may be ignored as far as choosing the most attractive alternative is concerned. Furthermore, it is often proper to employ a "with" and "without" approach. For example, this is done with backwater damage costs for each

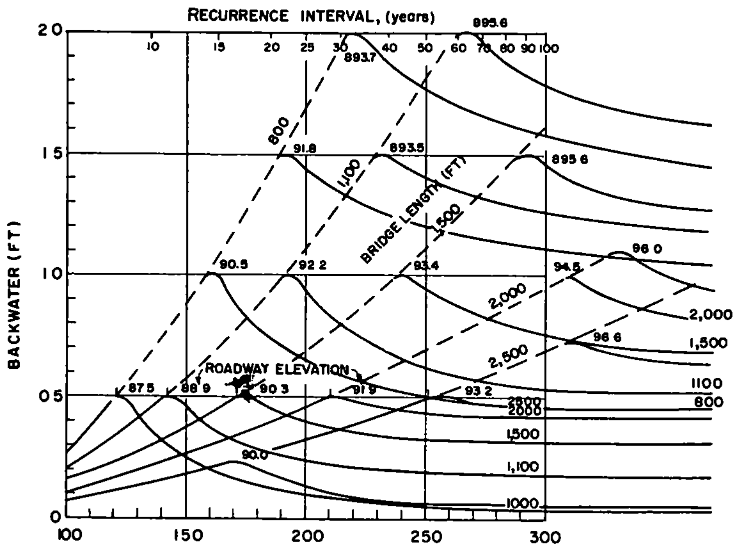

Figure 5. Flow with limited backwater for several bridge lengths (courtesy of J. N. Bradley).

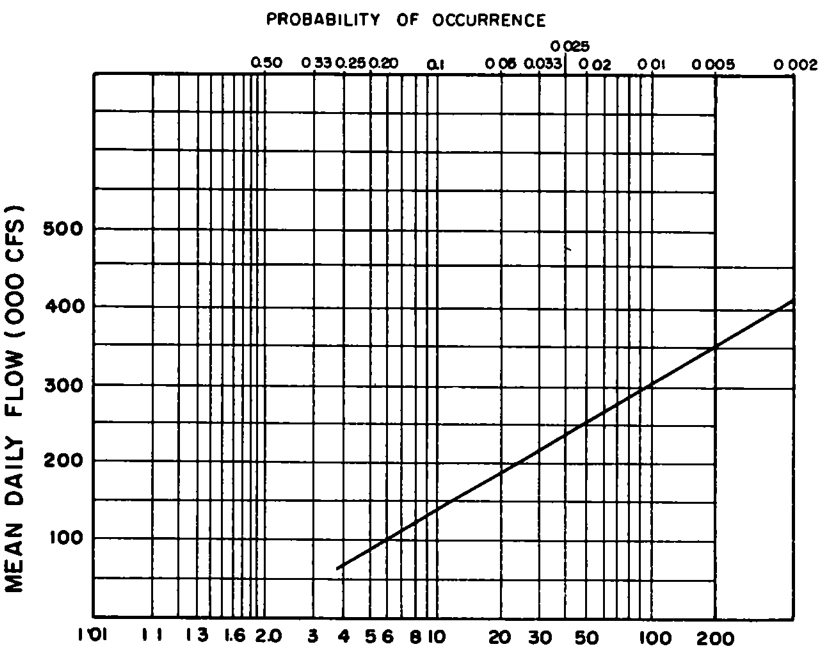

Figure 6. Frequency curve (assumed).

combination of bridge and embankment. With large floods, some damage will probably occur with no bridge at all; this is the base condition. Only the increment of damage resulting because of each bridge-embankment combination is pertinent and is computed.

Costs Related to Embankment Height

There are several annual costs included in most economy studies of approach embankments: (a) capital recovery for embankment, (b) embankment maintenance,

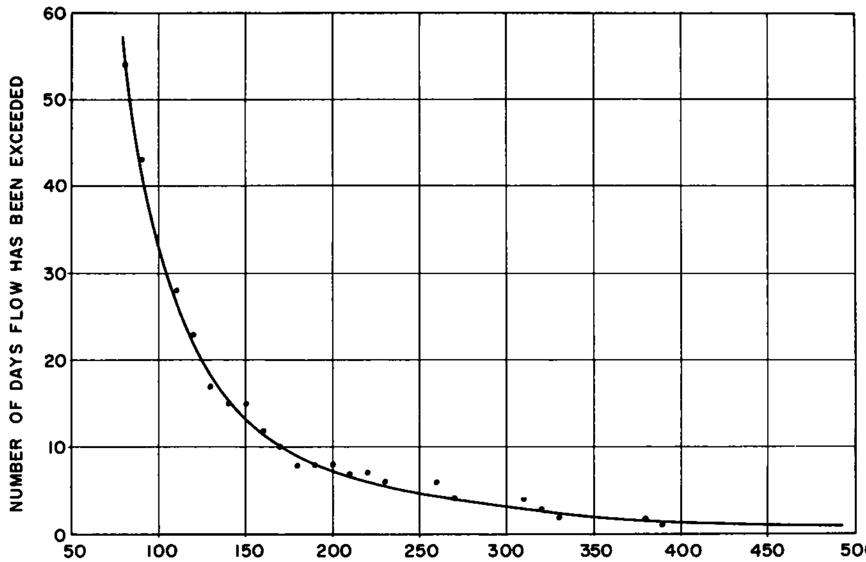

Figure 7. Number of days flow exceeded in past 50 years (courtesy of J. N. Bradley).

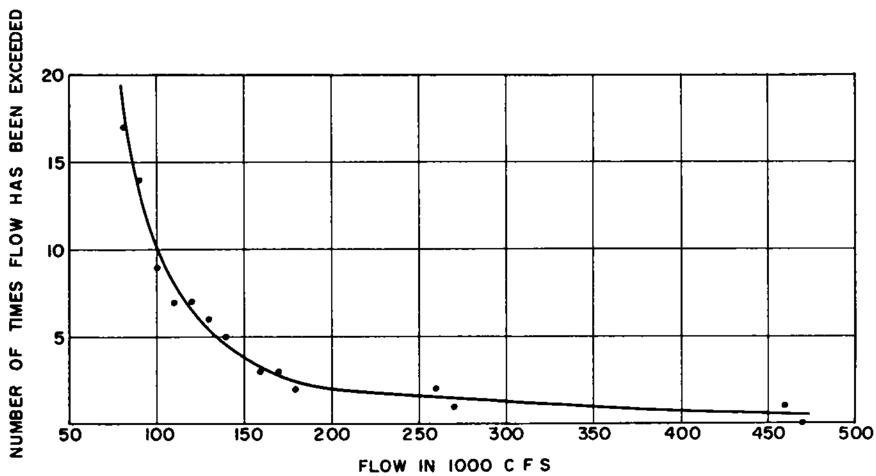

Figure 8. Number of times a flow exceeded in past 50 years (courtesy of J.N. Bradley).

(c) expected flood damage to embankment, (d) expected detouring, and (e) expected increment of backwater damage. Any other variables that might affect vehicle-operating or other costs in a particular case should also be included.

Method for Predicting Expected Average Annual Damage

A numerical procedure suggested by B. Franzini (6) is used to evaluate the annual expected flood damage. A typical annual probability-damage curve is shown as Figure 11. The probability axis is divided into elements P_1P_2----P_n. For each probability P_i there is a damage d_i. The area of a typical element 1-2 is given by

Elemental area 1-2 = $\left(\frac{D_1 + D_2}{2}\right)(P_2 - P_1)$. The sum of all elemental areas under the probability-damage curve is the expected annual cost. A method for summing these elemental areas is shown in Table 1.

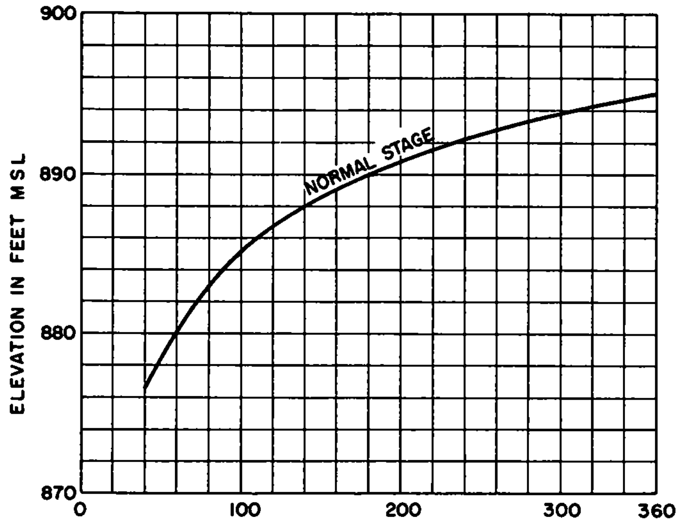

Figure 9. Stage discharge curve for river at bridge site (courtesy of J.N. Bradley).

Method of Computing Embankment Costs

Cost comparisons are made on an annual cost basis; each of the embankment costs is listed with a brief discussion and explanation of how it is computed.

Annual cost of capital recovery for embankment.—Annual cost = (first cost) x (crf-i-n), where First cost = Total cost of embankment and paving; (crf-i-n) = capital recovery factor for interest rate i and analysis period n. The example problems are solved at an interest rate of 7 percent, a period of 30 years for bridge and embankment and with zero salvage value (see Woods (5) or Grant and Ireson (7) for detailed procedures for economy studies and for compound interest tables.)

Annual embankment maintenance.—Embankment maintenance costs have been assumed to be proportional to embankment length. They were set at $0. 30 per lineal foot, based on maintenance cost figures supplied by G. S. Paxson of the Oregon Highway Department. This figure is approximate and may be low because it is not necessarily for embankments subject to flooding.

Annual expected embankment damage.—These costs are for repairing damage caused by flood flows overtopping the embankment. Anticipated annual costs decrease as embankment heights increase because overtopping of higher embankments is less frequent. For Example 1 damage costs were assumed to be 5 percent of the total embankment cost for each foot of flow energy head above the embankment roadway elevation.

Very little has been published concerning damage to embankments from overtopping. Kindsvater (8) reports how embankment damage by flood waters occurs and Yarnell and Nagler (9) give some examples of damages from flood flows.

The computation for embankment damage is an application of the method described earlier for evaluating annual expected damage. The embankment damage computation can be set up as shown in Table 2. (A sample calculation for this item combined with

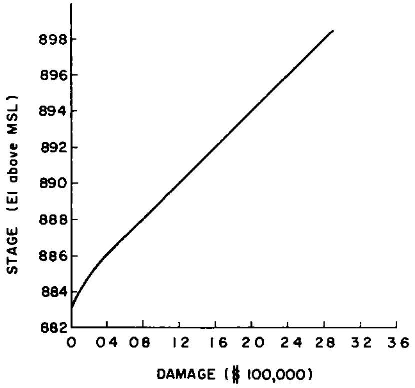

Figure 10. Stage-demand curve (assumed).

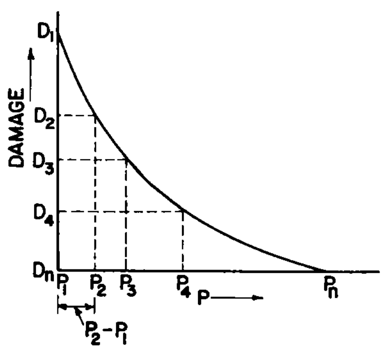

Figure 11. Probability-damage curve.

background information of Example 1 has been taken, for the most part, from materials supplied to the authors by Bradley (1). Example 2 employed the same methods; however, the specific problem was assumed by the authors of this paper.

The following items of information are needed before the economic analysis can be made.

1. Cross-section of the river and flood plain at the bridge site (see Figs. 1 and 14).
2. Bridge costs for the various bridge lengths. For preliminary studies such as these, cost might be roughly approximated as the sum of a fixed cost, plus a constant times the bridge length; e.g., for a bridge length L, bridge cost = a+bL, in which a = the sum of all fixed costs (abutments, etc.) and b = the cost per unit length for piers and superstructure. Bridge costs for Example 1 are plotted on the right-hand ordinate of Figure 2. For Example 2 they were assumed as $6,300 + $420 x bridge length (see Fig. 18).
3. Embankment costs for various bridge lengths and embankment elevations. Estimated costs have been plotted against embankment elevation with bridge length as a parameter (see Figs. 3 and 17).
4. Water surface elevation at the upstream embankment slope. Figure 4 shows this as a plot of water surface elevation discharge using length of bridge as a parameter. The method for calculating values for this plot is found in Bradley (1).
5. Bridge backwater. This is recorded in a plot showing bridge backwater without embankment overflow for a given river discharge and bridge length (see Fig. 2). The method for calculating values is found in Bradley (1).
6. Flow with limited backwater for bridges of several lengths. This is shown in a plot of backwater vs river discharge, with bridge length as a parameter (see Fig. 5). The data for the curves of backwater vs discharge without embankment overflow are the same as are found in Figure 2. To develop the portions of the curves to the right of their peaks, it is first necessary to choose a specific value for backwater height, which is the rise in the water surface resulting from the presence of bridge and embankment. The river discharge corresponding to that backwater height represents the flow at which the approach embankment is first overtopped. At higher discharges, the roadway acts as a broad crested weir with a head equal to the difference in elevation between the water surface (flow energy line) and the roadway elevation. The backwater height decreases after overtopping.

Most of the data on Figure 5 was supplied by Bradley. However, the authors approximated the curves sweeping downward to the right for backwaters at overtopping of 1.0, 1.5, and 2.0 ft. Further information on the flow of water over roadway embankments can be found in Sigurdsson (2) and Bradley (3). The backwater computation method is based on model tests conducted at Colorado State University for the Bureau of Public Roads.

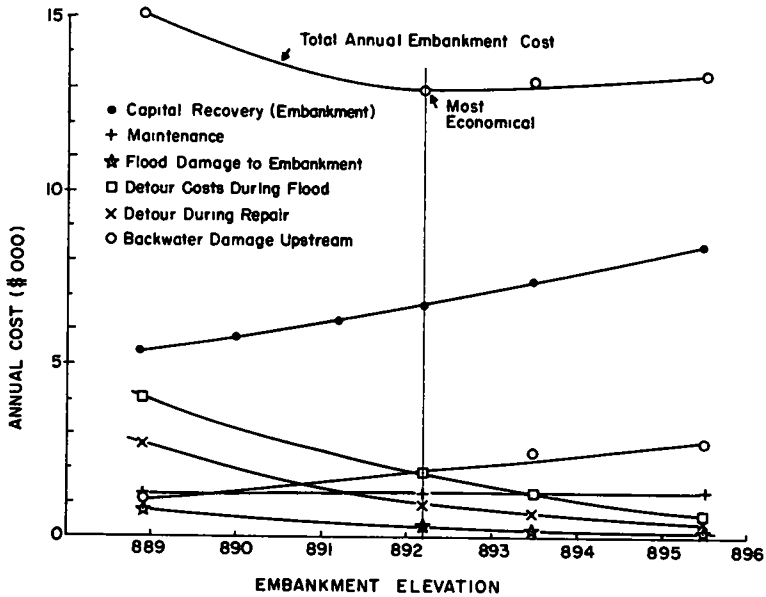

Figure 12. Embankment cost, 1,100-ft bridge.

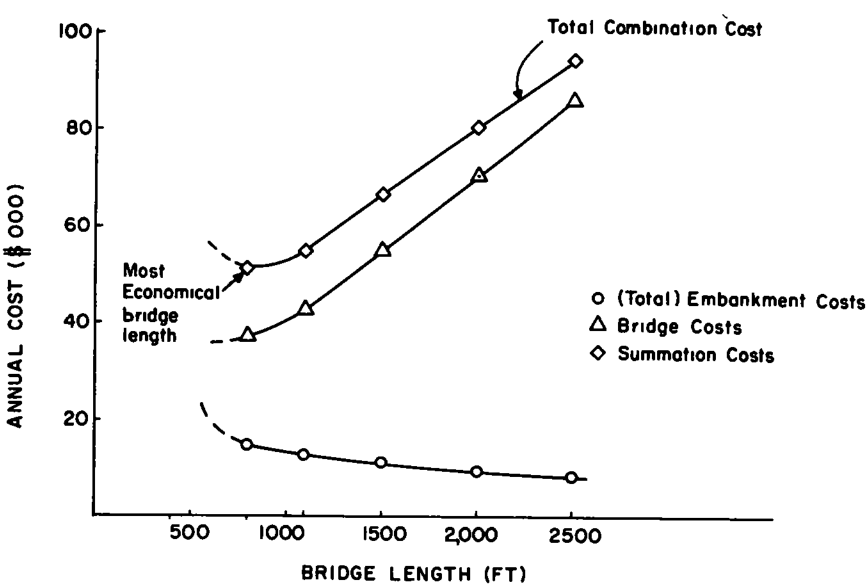

Figure 13. Combined annual cost of bridge and embankment.

Limitations

A few of the limitations of backwater computations, taken from Bradley (1), should be noted:

1. The method of computing backwater is intended for use with relatively straight reaches of streams with approximately uniform cross-section and slope.
2. The U. S. Geological Survey field measurements which were used to verify the application of the laboratory data to field conditions were limited to single bridges up to 220 ft in length on streams with a maximum width of ⅛ mi at flood stage. Verification for flood plains of much greater widths is lacking at the present time.

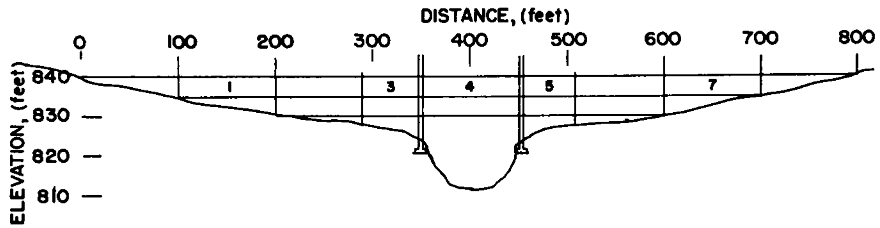

Figure 14. Section of river at bridge (example 2, short bridge).

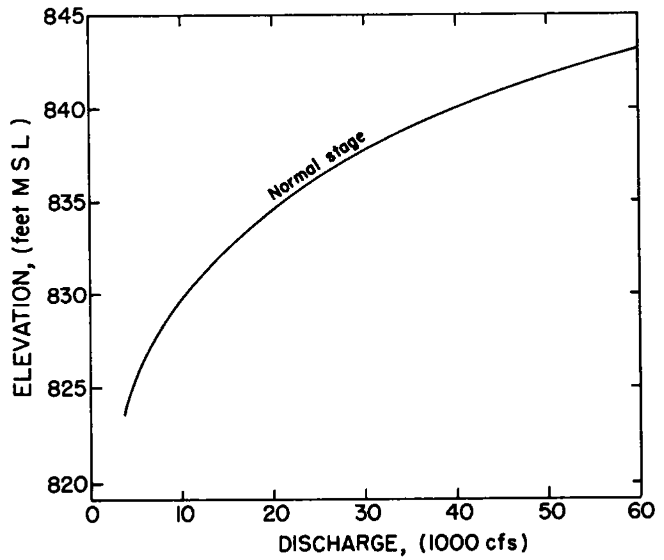

Figure 15. Stage-discharge curve (example 2, short bridge).

3. The computations for backwater assume no scour occurs at the bridge or embankment.

Frequency curve. —The frequency curve gives the probability of an equal or larger mean daily flow occurring in a given year. Figure 6, the assumed frequency curve for Example 1, is developed on Gumbel probability paper. However, any comparable method for finding probabilities is acceptable. In actuality, flow probabilities for a particular site would, if possible, be based on past stream flow records. For more information on frequency curves see Linsley et al. (4, pp. 555-559).

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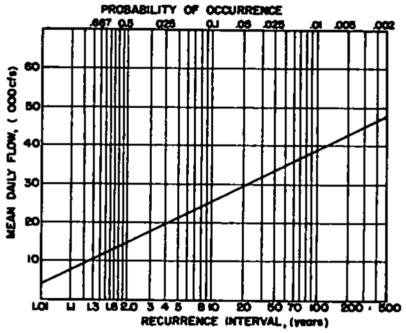

Figure 16. Frequency curve (example 2, short bridge).

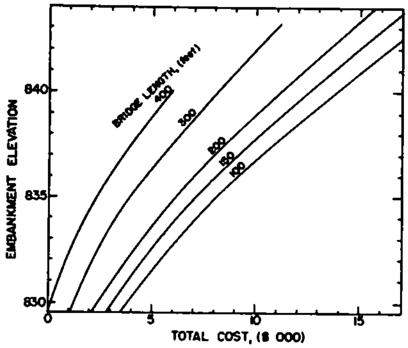

Figure 17. Total embankment costs includes embankment and paving (example 2, short bridge).

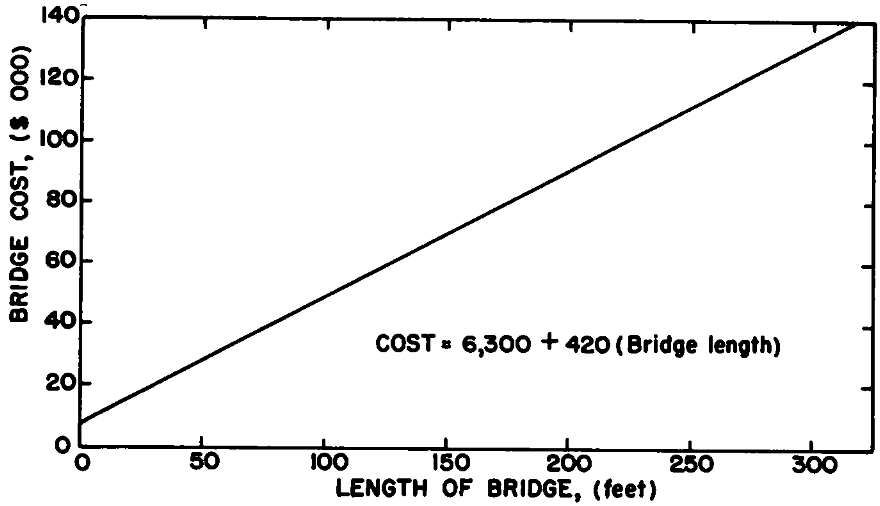

Figure 18. Bridge costs (example 2, short bridge).

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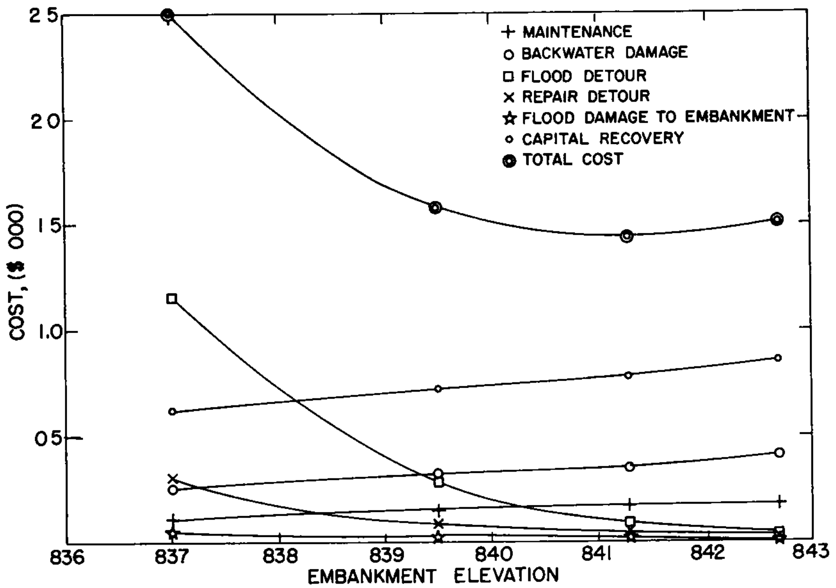

Figure 19. Embankment cost, 300-ft bridge (example 2).

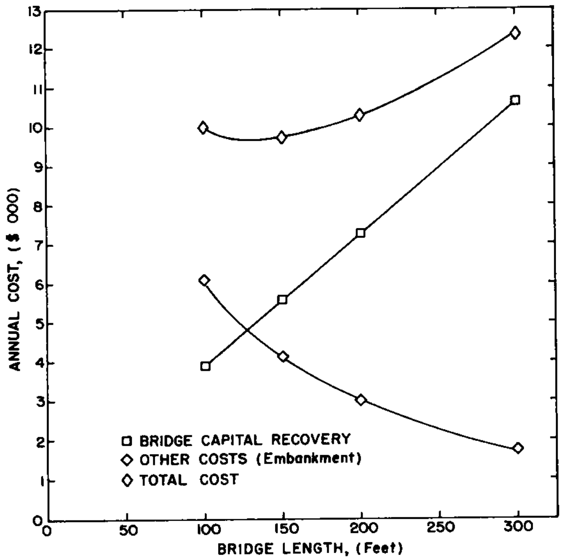

Figure 20. Combination-bridge and embankment costs (example 2, short bridge).

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$$\text{Elemental area 1-2} = \left(\frac{D_1 + D_2}{2}\right)(P_2 - P_1).$$

The sum of all elemental areas under the probability-damage curve is the expected annual cost. A method for summing these elemental areas is shown in Table 1.

Method of Computing Embankment Costs

Cost comparisons are made on an annual cost basis; each of the embankment costs is listed with a brief discussion and explanation of how it is computed.

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Annual expected embankment damage. -These costs are for repairing damage caused by flood flows overtopping the embankment. Anticipated annual costs decrease as embankment heights increase because overtopping of higher embankments is less frequent.

TABLE 1

COMPUTATION OF EXPECTED ANNUAL FLOOD DAMAGE

Damage D	$\frac{D_1 + D_2}{2}$	Probability, P	$(P_2 - P_1)$	$\frac{D_1 + D_2}{2}(P_2 - P_1)$
D_1		P_1		
	$\frac{D_1 + D_2}{2}$		$(P_2 - P_1)$	$\frac{(D_1 + D_2)(P_2 - P_1)}{2}$
D_2		P_2		
	$\frac{D_2 + D_3}{2}$		$(P_3 - P_2)$	
D_3		P_3		
				.
	$\frac{D_N - 1 + D_N}{2}$		$(P_N - P_N - 1)$	$\frac{D_{N-1} + D_N \; P_N - P_{N-1}}{2}$
D_N		P_N		

Expected annual damage = $\sum_{i=1}^{i=N-1} \frac{D_i + D_{i+1}}{2} \left(P_{i+1} - P_i\right)$

TABLE 2

COMPUTATION OF EXPECTED ANNUAL EMBANKMENT DAMAGE

Bridge Length	Emb Elev	Emb Cost	Bridge Stage No	Flow (cfc)	Stage at Embankment	Energy Head Above Embankment	Percent Damage to Embankment	Increment of Average Percent Damage	Increment of Average Damage Cost	Probability of flow Occurring	Increment Probability	Increment Embankment Damage
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)

Total annual embankment damage cost = $\sum$ (m)

TABLE 3

COMPUTATION OF EXPECTED ANNUAL DETOUR COSTS DURING EMBANKMENT REPAIR

Bridge Length	Embankment Elev	Flow (cfs)	Increment Average % Damage to Embankment	Increment Probability	Increment Average Time to Repair	Increment Average Detour Cost	Increment Detour Cost
(a)	(b)	(e)	(j)	(l)	(n)	(o)	(p)

Average annual detour cost during repair = $\sum$ (p)

TABLE 4

COMPUTATION OF EXPECTED ANNUAL COST TO DETOURED TRAFFIC

Bridge Length	Embankment Elev.	Flood Routing Stage	Flow (cfc)	Days Above Stage	Times Above Stage	Average Days per Time	Cost per Time	Probability of Occurrence	Expected Cost of Detoured Traffic
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)

TABLE 5

COMPUTATION OF EXPECTED ANNUAL INCREMENTAL OF BACKWATER DAMAGE CAUSED BY BRIDGE

Bridge Length	Embankment Elev.	Stage No. Bridge	Flow (cfc)	Increment of Backwater to Cause Damage	Incremental Backwater Damage	Average Incre-mental Damage	Probability of Occurrence	Incre-mental Proba-bility	Incre-mental Damage
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)

TA

SUMMARY AND RESULTS OF EX

	Row						
Bridge length (ft)	(A)	800	800	800	800	1,100	1,10
Max backwater (ft)	(B)	0 5	1 0	2 0	2 5	0 5	1
Embank elev (ft)	(C)	887 5	890 5	893 7	895 2	888 9	892
Embank length (ft)	(D)	4,400	4,500	4,600	4,625	4,150	4,250
Embank and paving cost ($)	(E)	61,000	76,000	92,500	103,000	64,750	82,700
Length of paving for equal length (ft)	(F)	225	125	25		175	75
Paving cost (at 50,000/mi) ($)	(G)	2,131	1,184	237		1,657	710
Total cost embankment paving ($)	(H)	63,131	77,184	92,737	103,000	66,407	83,410
Expected Annual Costs, embankment ($)							
Capital recovery, embank and paving	(I)	5,088	6,220	7,474	8,301	5,352	6,722
Embank maintenance (at $0 30/ft)	(J)	1,320	1,350	1,380	1,388	1,245	1,275
Flood damage to embankment	(K)	1,221	605	239	167	777	276
Detour during repair	(L)	3,876	1,846	728	463	2,698	934
Detour during flood	(M)	4,995	3,042	1,261	764	4,004	1,800
Increment backwater damage	(N)	866	2,132	3,394	3,725	1,055	1,850
Total	(O)	$ 17,366	15,195	14,476	14,808	15,131	12,85
Expected annual costs, embank and bridge							
Bridge length (ft)	(P)	800	1,100	1,500		2,000	2,
Bridge cost ($)	(Q)	460,000	525,000	680,000		875,000	1,070,
Length of combination (ft)	(R)	5,400	5,350	5,375		5,400	5,
Length of pave for equal length (ft)	(S)	0	50	25		0	
Capital recovery of bridge invest ($)	(T)	37,071	42,310	54,801		70,516	86,
Added pave (capital recovery) (Length x 9 4,797/ft x 0 08059) (crf - 7% - 30)	(U)	0	38	19		0	
Bridge maintenance at $0 $0/ft	(V)	160	220	300		400	
Embankment ($)	(W)	14,476	12,857	11,518		9,730	8,
Total ($)	(X)	51,707	55,425	66,638		80,646	95,
Present worth (pwf - 30 - 7%) = 12 409	(Y)	$641,632	687,769	826,910		1,000,736	1,178,

SUMMARY AND RESULTS O

	Row				
Bridge length (ft)	(A)	100	100	100	10
Max backwater (ft)	(B)	0.5	1.0	1.5	
Embank elev (ft)	(C)	834.7	837 3	839.7	84
Embank. length (ft)	(D)	490	600	690	75
Embankment cost (including paving) ($)	(E)	7,750	10,700	13,500	15,50
Paving needed for equal length projects (ft)	(F)	310	200	110	5
Paving cost (at $50,000/mi) ($)	(G)	2,939	1,896	1,043	47
Total cost embankment and paving ($)	(H)	10,689	12,596	14,543	15,97
Expected annual costs, embankment ($),					
Capital recovery (embankment and paving) (crf-7%-30 = 0 08059)	(I)	861	1,015	1,172	1,28
Embankment maintenance (at $0 30/ft)	(J)	117	180	207	21
Flood damage to embankment	(K)	214	109	64	5
Traffic interruption during embankment repair (based on $5,000 for detour/day)	(L)	1,265	573	285	19
Traffic interruption during flood (based on $5,000 per detour/day)	(M)	3,400	1,530	712	29
Increment backwater damage	(N)	1,733	3,189	3,740	3,94
Total	(O)	7,590	6,596	6,180	5,98
Expected annual costs, embankment and bridge					
Bridge length (ft)	(P)	100	150	200	30
Bridge cost ($)	(Q)	48,300	69,300	90,300	123,30
Combination length (ft)	(R)	900	950	960	91
Length of pavement for equal length (ft) added pavement ($)	(S)	60	10	-	5
		569	95	-	47
Bridge capital recovery (crf-7%-30 = 0 08059) ($)	(T)	3,892	5,585	7,277	10,66
Added pavement capital recovery ($)	(U)	46	7	-	3
Bridge maintenance (at $0 50/ft)	(V)	50	75	100	15
Embankment ($)	(W)	5,989	4,012	2,839	1,43
Total ($)	(X)	9,977	9,679	10,216	12,28
Present Worth (pwf-30-7%) = 12 409 ($)		123,805	120,107	126,770	152,44

6

LE PROBLEM 1 (LONG BRIDGE)

,100	1,100	1,500	1,500	1,500	2,000	2,000	2,000	2,500	2,600	2,500	2,500
1 5	2 0	0 5	1.0	1 5	0 5	1.0	1 1	0 23	0 5	0 75	1 0
893 5	895.5	890 3	893.4	895.6	891 9	894.5	896 0	890 0	893 2	895 0	896 6
275	4,325	3,800	3,875	3,950	3,350	3,400	3,450	2,775	2,850	2,900	2,950
750	103,000	66,750	84,000	98,500	67,750	81,750	91,000	53,500	65,200	74,000	82,000
50		150	75		100	50		175	100	50	
473		1,420	710		947	473		1,657	947	473	
223	103,000	68,170	84,710	98,500	68,697	82,223	91,000	55,157	66,147	74,473	82,000
352	8,301	5,494	6,827	7,938	5,536	6,626	7,334	4,445	5,331	6,002	6,608
282	1,297	1,140	1,162	1,185	1,005	1,020	1,035	832	855	870	885
205	105	445	159	82	238	82	59	371	112	59	44
691	356	1,568	566	249	800	234	154	1,592	423	214	133
225	576	3,089	1,040	470	1,604	576	246	3,042	930	333	80
410	2,682	1,386	1,764	2,026	976	1,192	1,204	462	726	800	832
165	13,317	13,122	11,518	11,950	10,159	9,730	10,032	10,744	8,377	8,278	8,582

BLE 7

AMPLE PROBLEM 2 (SHORT BRIDGE)

100	150	150	150	200	200	200	300	300	300	300
2.5	1.0	1 5	2.0	0.5	1.0	1.5	0.1	0.2	0.3	0.4
842.3	839.3	841 5	843.7	838 3	841.8	844.0	837.0	839.5	841.3	842.7
800	620	710	800	530	670	760	380	480	560	610
,700	11,800	14,250	16,900	9,300	13,300	15,700	5,500	7,750	9,300	10,700
-	180	90	-	230	90	-	230	130	50	-
-	1,706	853	-	2,180	853	-	2,180	1,232	474	-
,700	13,506	15,103	16,900	11,480	14,153	15,700	7,680	8,982	9,774	10,700
,346	1,088	1,217	1,362	925	1,141	1,265	619	724	788	862
270	186	213	240	159	201	228	114	144	168	183
56	37	24	25	35	20	8	41	15	9	8
175	193	88	71	226	65	23	303	81	36	24
178	510	157	46	690	83	20	1,160	284	88	32
,089	2,124	2,313	2,363	1,166	1,329	1,346	258	326	346	403
,114	4,138	4,012	4,107	3,201	2,839	2,890	2,495	1,574	1,435	1,512

TABLE 8

SAMPLE COMPUTATION FOR PROBLEM 1 (1,100-FT BRIDGE), COST OF FLOOD TO EMBANKMENT AND OF DETOUR COSTS DURING REPAIRS[1]

Bridge Length (ft)	Embankment Elev. (ft)	No Bridge Stage	Q (000 cfs)	Stage at Embankment	Water Head over Embankment	% of Damage to Embankment	Ave % Damage to Embankment	Ave Damage Costs ($)	Ave Time to Repair (days)	Ave Detour Costs	Prob of Occurrence	Increment Probability	Increment Emb Damage ($)	Increment Detour Costs ($)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1,100	888 9		140	888 9	0	0					0.10			
							5 8	3,756	0.58	5,800		0.065	244	377
		891 0	205	891 22	2 32	11 6					0 035			
							14 05	9,097	1 405	14,050		0 005	45	70
		892 0	235	892 20	3 30	16 5					0 030			
							18 95	12,270	1 895	18,950		0 013	160	246
		893 0	270	893 18	4 28	21 4					0 017			
							23 9	15,475	2 39	23,900		0 008	124	191
		894 0	310	894 18	5 28	26 4					0 009			
							28 9	18,713	2 89	28,900		0 005	94	144
		895 0	360	895 18	6 28	31 4					0 004			
							33 9	21,950	3 39	33,900		0 003	66	102
		896 0	450	896 18	7 28	36 4					0 001			
							68 2	44,159	6 82	68,200		0 001	44	68
			largest	-	-	100 0					0 0			
											Total		777	1,198

[1]Embankment cost = $64,750

TABLE 9

SAMPLE COMPUTATION FOR PROBLEM 1 (1,100-FT BRIDGE) DETOUR COSTS DURING FLOOD

Bridge Length (ft)	Embankment Elev (ft)	Routing Stage of Bridge	Flow (000 cfs)	Days Above Stage	Times Above Stage	Average Days per Time	Cost per Time ($000)	Probability of Occurrence	Cost of Detoured Traffic ($)
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
1,100	888 9	887 9	129	18 2	5	3 64	3 64	0 11	4,004

TABLE 10

SAMPLE COMPUTATION FOR PROBLEM 1, (1,100-FT BRIDGE), INCREMENT OF BACKWATER DAMAGE CAUSED BY BRIDGE

Bridge Length (ft)	Embankment Elev (ft)	No Bridge Stage	Flow (000 cfs)	Increment of Backwater to Cause Damage	Incremental Backwater Damage	Average Damage ($)	Probability of Occurrence	Incremental Probability	Incremental
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
1,100	888 9	883 0	80	0 1	0		0 20		
						2,600		0 06	156
		886.0	110	0 26	5,200		0 14		
						7,600		0 04	304
		888 0	140	0 5	10,000		0 10		
						7,200		0 065	468
		891 0	205	0 22	4,400		0 035		
						4,200		0 005	21
		892 0	235	0 20	4,000		0 030		
						3,800		0 013	50
		893 0	270	0 18	3,600		0 017		
						3,600		0 008	28
		894 0	310	0 18	3,600		0 009		
						3,600		0 005	18
		895 0	360	0 18	3,600		0 004		
						3,600		0 003	10
		896 0	450	0 18	3,600		0 001		

Estimated Annual Backwater Damage = $1,055

TABLE 11

SUMMARY OF EFFECT OF EMBANKMENT HEIGHT ON VARIOUS EMBANKMENT COSTS

Embankment	Embankment Cost	Maintenance Cost	Damage to Embankment	Traffic Routing Costs	Increment Backwater Costs
High	Higher	Higher	Lower	Lower	Higher
Low	Lower	Lower	Higher	Higher	Lower

TABLE 12

COMPARISON OF ESTIMATED COSTS FOR BRIDGES OF VARIOUS LENGTHS

Bridge Length (ft)	Total Expected Annual Cost ($)	Present Worth ($)	Percent Savings of Most Economical Bridge
Example 1:			
800	51,710	641,630	0.00
1,100	55,430	687,770	7.20
1,500	66,640	826,910	28.9
2,000	80,650	1,000,740	56.0
2,500	95,010	1,178,970	83.8
Example 2:			
100	9,980	123,810	3.1
150	9,680	120,110	0.0
200	10,220	126,770	5.5
300	12,290	152,450	26.9

For Example 1 damage costs were assumed to be 5 percent of the total embankment cost cost for each foot of flow energy above the embankment roadway elevation.

Very little has been published concerning damage to embankments from overtopping. Kindsvater (8) reports how embankment damage by flood waters occurs and Yarnell and Nagler (9) give some examples of damages from flood flows.

The computation for embankment damage is an application of the method described earlier for evaluating annual expected damage. The embankment damage computation can be set up as shown in Table 2. (A sample calculation for this item combined with detour costs, appears as Table 8.) Explanation of Table 2 where the headings may not be fully descriptive are as follows:

Col. (c) Embankment costs taken from Figure 3.

Col. (d) No bridge stage. These are water surface elevations without the bridge and embankment. They are computed for selected values of Q (flow) as given in Col. (e) see Fig. 9).

Col. (f) Stage at embankment is found in two steps. First, the rise in the water surface resulting from backwater after the fill is overtopped is read from Figure 5, for this appropriate roadway (approach fill) elevation and bridge length. This value is added to the water-surface elevation, without bridge, as shown in Col. (d). It is an approximation of the flow energy line because Figure 4 is computed without embankment overflow.

Col. (g) Head above the embankment is the stage at the embankment minus the embankment elevation:

Col. (g) = Col. (f) - Col. (b).

Col. (h) Percent damage to embankment is an assumed constant stated as percent damage per foot of energy head above embankment times the head above the embankment (Col. g).

Col. (h) = k. Col. (g) in which k = percent damage per foot energy head above embankment.

Col. (i) Increment of average percent damage is the average between the successive rows in Col. (h).

$$\text{Col. } (i)_{1-2} = \frac{\text{Col. } (h)_1 + \text{Col. } (h)_2}{2}$$

Col. (j) Increment of average embankment damage cost is the average percent damage times the cost of the embankment.

Col. (j) = Col. (i) x Col. (c).

Col. (k) Probability of flow occuring is taken from the frequency curve (Fig. 6) for the flows found in Col. (e).

Col. (l) Incremental probability is the difference between successive rows of flow probabilities.

$$\text{Col. } (l)_{1-2} = \text{Col. } (k)_1 - \text{Col. } (k)_2.$$

Col. (m) Incremental embankment damage is the product of the increment average damage times the incremental probability.

Col. (m) = Col. (j) x Col. (l).

Expected annual flood damage to the embankment is the sum of all incremental embankment damages.

$$\begin{matrix}\text{Annual}\\ \text{Embankment}\\ \text{Damage}\end{matrix} = \sum_{i=1}^{n} \text{Col. } (m)_1$$

Annual expected detour costs. -Detour occurs when flood waters are of sufficient stage that traffic cannot cross the bridge and embankment. The delays caused by flood are divided into three types: (a) flood detour, (b) recession detour, and (c) repair detour.

Traffic rerouting is assumed to occur when the flood waters reach an elevation somewhat below the embankment roadway elevation. Any time that a flood is above this stage traffic is to be detoured. The cost of routing vehicles during these flood stages is computed separately under the heading of annual expected detour cost during flood.

If the flood has a stage above the roadway elevation, it is assumed to cause embankment damage. If damage occurs, traffic will be detoured during the time the flood recedes from the flood detour elevation to the elevation where repair can take place (recession detour) and also during the time of repair (repair detour). Recession and repair detours are closely related so both are included in the computation of annual expected detour cost during embankment repair.

Annual expected detour costs during embankment repair. - The detour cost during embankment repair is the added cost for vehicles and drivers caused by the detour plus detour set-up and maintenance costs. The detour time in this paper was assumed to be directly proportional to the damage. For instance, in Example 1, the detour time was assumed as 1 day for each 10 percent embankment damage. The traffic detour cost per day was set as a flat sum; no detailed computations were made for it.

Repair detour costs and embankment damage costs can be computed in the same table. The detour cost computation columns are shown separately in Table 3 in order that the procedure can be followed more easily. Table 8 is a calculation from Example 1; this shows how Tables 2 and 3 look when combined.

The computation procedure for Table 3 is described as follows:

Columns (a), (b), (e), (j), and (l) are taken from Table 2, Annual Expected Embankment Damage.

Col. (n) Incremental average time to repair is the product of the incremental average percent damage to the embankment times the time to repair for a given percent damage.

Col. (o) Incremental average detour cost is the product of the incremental average time to repair times the cost per day of detour.

Col. (p) Incremental detour cost is the product of the incremental probability times the incremental average detour cost.

$$\text{Col. (p)} = \text{Col. (l)} \times \text{Col. (o)}.$$

Total annual expected detour cost is the sum of all figures in Col. (p) plus the annual expected cost of detour while the flood causing damage is receding before repair (recession detour).

The recession cost was assumed to be the product of the detour costs during the time the flood recedes multiplied by the annual probability of having a flood of magnitude to cause damage. The recession time is the time for the flood water to recede from flood detour elevation to an elevation where embankment repair can begin. This time was assumed as constant in the examples.

$$\left(\begin{array}{c}\text{Recession}\\ \text{Cost}\end{array}\right) = \left(\begin{array}{c}\text{time for}\\ \text{recession}\end{array}\right)\left(\begin{array}{c}\text{cost/unit for}\\ \text{detour time}\end{array}\right)\left(\begin{array}{c}\text{annual probability of}\\ \text{damage occurring}\end{array}\right)$$

For instance, in Example 1 of this paper, the time to recede is assumed as $1\frac{1}{2}$ days at a cost for detouring of \$10,000 per day. Thus the expected annual cost of detouring is \$15,000 times the probability of a flood of stage above the embankment roadway elevation. For example, the \$2,698 shown in Col. 5 under Item (L) in Table 6 equals the sum of \$1,198 from Col. (15) of Table 8 and \$15,000 x 0.10.

Annual expected traffic detour costs during floods. - The annual cost of detouring during floods is the product of the annual probability of having a flood equal to or higher than the flood routing stage times the cost per occurrence of detouring for the days above this stage. The number of days a flow has been exceeded (see Fig. 7) and the number of times a flow has been exceeded (see Fig. 8) and the detour cost per day will be available.

The computation form for annual expected detour cost during floods is shown in Table 4 and Table 9. The columns are described as follows:

Col. (c) Flood routing stage is the flow when detouring begins. This detouring begins when the water surface at the embankment is some assumed distance below the elevation of the embankment.

Col. (d) Flow is taken from the water surface elevation at the upstream embankment slope curve (Fig. 4).

Col. (e) Days above stage is taken from Figure 7 for the flow given in Col. (d).

Col. (f) Times above stage is taken from Figure 8 for the flow given in Col. (d).

Col. (g) Average days per time is the ratio of days exceeded per flow to times exceeded per flow.

$$\text{Col. (g)} = \text{Col. (e)} \div \text{Col. (f)}.$$

Col. (h) Cost per time is the product of detour days per time (Col. g) times the cost of detouring per day.

$$\text{Col. (h)} = c \text{ times Col. (g)},$$
$$\text{where } c = \text{cost/day of detouring.}$$

Col. (i) Probability of occurrence is taken from the flood frequency curve (Fig 6) for the flow in Col. (d).

Col. (j) Expected annual cost of detouring traffic because of flood is the product of the cost per time (Col. h) times the probability of occurrence.

$$\text{Col. (j)} = \text{Col. (h)} \times \text{Col. (i)}.$$

Annual expected incremental backwater damage cost. – This cost is the difference in damage costs between the annual expected flood damage that would occur with a given bridge and approach embankment and the annual expected flood damage in the natural stage without the bridge.

Calculation of the backwater damage cost is another evaluation of the annual expected damage by numerical integration. The calculation form for backwater damage cost is shown in Table 5 (see Table 10 also). The various columns in Table 5 are described as follows:

Col. (c) Stage without bridge is the normal stage (see Fig. 9).

Col. (d) Flow is for the stages found in Col. (c).

Col. (e) Increment of backwater to cause damage is found from Figure 5. After the flood stage reaches embankment elevation, the backwater effect will follow the receding curve for increased flows.

Col. (f) Incremental backwater damage is the difference between the damage for the stage with incremental backwater Col. (e) plus normal stage Col. (c) and the damage at normal stage Col. (c). These damages are found from the stage-damage curve (Fig. 10) for the respective stages.

Col. (g) The average incremental damage is the average of successive rows in Col. (f).

$$\text{Col. (g)}_{1-2} = \frac{\text{Col. (f)}_1 + \text{Col. (f)}_2}{2}$$

Col. (h) Probability of occurrence is the probability of the flows in Col. (d). This is taken from the frequency curve (Fig. 6) for the respective flows.

Col. (i) Incremental probability is the difference between successive rows of flow probabilities.

$$\text{Col. i} = (\text{Col. h})_1 - (\text{Col. h})_2$$

Col. (j) Incremental damage is the product of the average incremental damage (Col. g) times the incremental probability (Col. i).

$$\text{Col. (j)} = \text{Col. (g)} \times \text{Col. (i)}.$$

The total incremental backwater damage caused by the bridge and embankment is the summation of incremental damages found in Col. (j).

$$\text{Backwater damage} = \sum_{i=1}^{n} \text{Col. (j)}_i$$

Method for Finding the Most Economical Embankment Height

The procedure for finding the most economical embankment height for a given bridge length is to choose the embankment heights to be compared, evaluate the various embankment costs for these heights (see Table 6), and plot embankment height vs cost (see Fig. 12). The most economical embankment will be the minimum point on the summation curve. If the most economical embankment height is not included in those for which costs have been developed it may be necessary to compute the costs of other embankment heights. Finally, the costs of the most economical embankment height are evaluated as a check, by using the normal calculation methods for finding embankment costs. To illustrate, for the 1,100-ft bridge in Example 1, embankment costs for an elevation of 892.2 can be computed to be $12,860, which checks Figure 12.

Costs Affecting the Most Economical Combination of Bridge Length and Embankment Height

There are two bridge costs that will be common to all economy studies: (a) annual capital recovery cost of bridge and (b) annual bridge maintenance cost. Methods for evaluating these have already been outlined.

Total costs for a given alternative bridge length are the sums of embankment costs plus bridge costs. Because the total length of bridge plus embankment roadway for the compared alternatives must be the same, a length of roadway must be added to the shorter alternatives to make the compared project lengths equal. The capital recovery cost of extra pavement is added to the other bridge costs. Often the added pavement cost is small and may be ignored.

Selection of the Most Economical Alternative

The lower portion to Table 6 summarizes total and annual costs for the most economical combination of bridge and embankment. In it the annual costs of the least costly embankment for each bridge length is combined with the annual costs associated with the bridge (and added pavement length). The combination with the least total annual cost is most desirable from an economy point of view.

ANALYSIS

Findings of this study favor the 800-ft bridge in Example 1 and the 150-ft bridge in Example 2. As stated earlier, there well may be "irreducibles" that cannot be put in money terms. The final choice of bridge length will be made by weighing both the "dollar considerations" outlined here along with other important factors.

The graphs for embankment costs (Figs. 12 and 19) show that costs increase quite slowly with small departures from the economical embankment height. This indicates, for these examples at least, that embankments a foot or so higher or lower than the "most economical" represent acceptable alternatives. Table 11 summarizes the effects of embankment height on the individual cost items that make up total embankment costs. Such a table may prove useful in selecting embankment height for the final design.

Bridge length, the other principal variable in the analysis, makes a significant difference in total annual cost. This is indicated clearly by Table 12. Results of both examples favor short rather than long bridges. It would seem that in spite of the many uncertainties in the data on which the analysis is based, such a study warrants the time and effort it requires, particularly if it questions present practices.

In the two examples, the effects of channel scour resulting from high velocities were not considered in the calculation of bridge backwater nor in the economy study. This might be an important design or cost factor in some instances. For example, velocities under a short bridge with high approach embankments might be so great as to require expensive channel and slope protection. The overtopping of low approach fills reduces the velocities under the bridge and therefore reduces scour. Even so, where velocities are high enough to threaten stream bed or embankment erosion, the analysis must be modified to recognize design changes and cost factors. Bradley (1) has a discussion on the effects of scour and how to allow for it in backwater computations.

The authors have concentrated on developing an economy-study procedure. They recognize that this procedure involves a considerable amount of routine computation. However, with electronic computers readily available to carry out such manipulations, computation time becomes of little importance.

CONCLUSIONS

An economy study, basically the same as the one in this paper, could be used to good advantage in the design of many bridge and approach embankment combinations. The writers acknowledge that some of the methods proposed here for evaluating costs are at best approximate. Often they were assumed without supporting data. It is to be presumed that other more direct and accurate ways of obtaining them are available to engineers in the various highway agencies; if so, these better methods should be used. However, the principles for the economy study remain the same.

A literature search indicates that research is needed at least in three areas before reliable cost data will be available for studies such as these:

1. A sound basis on which to evaluate flood damages so that reliable stage-damage curves can be constructed. Joint efforts with other agencies concerned with this problem should be fruitful.
2. More knowledge of the behavior of embankments when they serve as spillways so that reliable estimates of first cost and damage can be made.
3. Better measures for determining the market and extra market costs that accompany rerouting of or delays to traffic. Considerable work is currently under way in this field and results should be forthcoming in the near future.

It is to be observed that the importance of items 1 and 3 is minimized on low-volume highways in rural areas. Thus, an analysis such as proposed here, supported by the underlying hydrologic and hydraulic studies, seems particularly appropriate for major bridges on rural farm to market and other secondary roads.

All things considered, efforts towards collecting the supporting data and in making economy studies such as proposed in this paper should lead to better grounds for decision making by highway engineers.

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To a large degree, the examples employed in this paper came from materials provided by J. N. Bradley of the U. S. Bureau of Public Roads. Other writings by him provide the techniques for computing backwater characteristics at bridge sites. Also, a procedure developed by J. B. Franzini of Stanford University has been employed to translate stage-damage relationships into an annual expected cost of flood damage. The significant contribution of these techniques toward the solution offered in this paper is gratefully acknowledged.

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Discussion

GENE E. WILLEKE, Hydraulic Research Engineer, Division of Hydraulic Research, Bureau of Public Roads. —It is refreshing to have a highway problem in which hydrology is less uncertain than some of the other factors.

One point that stands out very clearly is the insensitivity of change in backwater to a change in bridge length. A considerable change in bridge length has a small effect on the amount of backwater. The experimental errors inherent in the development of the procedure for computation of backwater would lead one to question a bridge length determination based on such a procedure. This is especially true in the case of the examples given in this paper in which all costs other than capital recovery and routine maintenance for the long bridge amount to less than 11 percent of the total cost. The same figure for the short bridge is less than 27 percent.

Although all the figures are quite fictitious, the evidence presented would certainly indicate that backwater computations are a poor criterion for bridge length determination and that a search for better criteria is in order.