Tentative Design Procedure for Riprap-Lined Channels—Field Evaluation

by

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INDIVIDUAL ACKNOWLEDGMENTS

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SUMMARY

The objective of NCHRP Project 15-2 has been to establish criteria and develop procedures for the design of armored channels. The first phase of the project resulted in NCHRP Report 108, "Tentative Design Procedure for Riprap-Lined Channels" (1), which describes procedures for designing such channels and proportioning the riprap so as to minimize erosion. The second phase has been a field evaluation of channels designed in accordance with these procedures. Since this report was completed, five such channels have been proposed, of which four have been constructed and one is in the planning stage. Two of the four completed channels have been subjected to discharges that approached the design discharges and hence provided reasonably definitive tests. Both channels appeared to be stable and in good condition after the floods. Although these results are somewhat sparse, it appears that drainage channels designed according to the proposed procedures will convey design discharges without significant erosion.
Chapter 1. INTRODUCTION AND RESEARCH APPROACH

As a result of the basic study outlined in the previous report (1)*, a field evaluation of riprap-lined channels designed in accordance with the procedures outlined therein was recommended to determine the effectiveness of the procedures at scales considerably larger than any that can be produced in the laboratory.

Because drainage channels are constructed as the need arises, and the necessity for a riprap lining depends on the local circumstances, considerable time may elapse before a substantial number of channels is available for examination. In addition, hydrologic events of the magnitude necessary to provide an effective test of the riprap's stability are relative infrequent. These conditions have militated against collection of sufficient data to thoroughly test the procedures developed in the study. Specifically, five channels have been proposed since the completion of the report outlining these design procedures; four of these have been constructed and one is still in the planning stage. Of the four completed projects, two were intended for stream relocations involving relatively large discharges and two are roadside drainage ditches. Some data have been obtained for these four channels, but in only two cases has the discharge been large enough to approach the design discharge and provide a reasonably definitive test. A detailed description of each of these channels and the available data on the results of the discharges which have occurred are given in the appendices.

Following completion of the previous report a letter of inquiry was sent to each of the regional hydraulic engineers of the Federal Highway Administration and to all members of the Highway Research Board Committee on Surface Drainage of Highways to alert these individuals to the completion of the report and suggest that representative future drainage channels be designed in accordance with these procedures. It was hoped that field observation of these channels could then be undertaken to evaluate the appropriateness of the proposed design techniques. A form (Figure 1) that could be used to record pertinent field data for any hydrological event that might occur during the life of a particular channel was also sent.

With the passage of time it is expected that additional channels will be designed on the basis of the proposed procedures, but because of imminent project termination, the evaluation study was limited to the channels described in the following.

The reasons for the proposed design procedures and the basis for their development can be summarized as follows:

Whenever highway construction interferes with the natural flow of water, erosion-resistant drainage channels must be designed and built to redirect the water to a natural waterway. A protective lining is usually required to prevent damage to the channel. The most extensively used protective linings are turf cover, by sodding or other methods, and various types of pavement. These linings are quite effective for a wide variety of conditions, but have certain limitations; for example, (1) turf cover is difficult to establish in arid areas and over sandy soil; (2) turf

*References are listed on page 33.
FIELD EVALUATION - RIPRAP-LINED DRAINAGE CHANNELS

NCHRP Project 15-2: Design to Control Erosion in Roadside Drainage Channels

ORIGINAL DESIGN

1. Design discharge cfs
2. Design slope ft per ft
3. Plan and sections as designed (drawings if available)
4. Longitudinal profile (drawings if available)
5. Size of riprap (50 per cent size) ft
6. Grading specification (if any)
7. Contributory drainage area, sq miles
8. Character of drainage area (cover, shape, etc.)
9. Soil type under riprap
10. Alternatives considered

CONSTRUCTION

1. Cross sections as constructed
2. Size of riprap as constructed
3. Construction procedures for riprap, placing, grading, compacting, etc.
4. Contract or force account
5. Cost of material
6. Cost of construction
7. Comments

FIELD DATA (for each storm)

1. Peak discharge (if available) cfs
2. Maximum depth ft
3. Rainfall (amount and intensity)
4. Stability of channel riprap (photographs)
5. Photographs and other descriptive matter
6. Diary of events and comments

Figure 1. Data form used for field evaluation.
cover is effective only with relatively low flow velocities; (3) paved ditch linings are usually difficult to construct and rather costly; and (4) paved ditch linings require extensive maintenance at times due to undercutting. As a result there has been a need for a type of economical protective lining for roadside channels suitable for conditions intermediate between those for which turf cover performs satisfactorily and those for which paved channels are more economical. The objective of the study mentioned previously was the development of criteria and design procedures for the use of aggregate or riprap linings for this intermediate category.

This was accomplished by synthesizing the principles of open-channel flow with the results of experimental data on the critical boundary shear and resistance due to the flow on a bed of discrete particles. By use of the information that had been reported in the literature and the inter-relationships between the discharge, slope, size, and shape of the channel and the size of the riprap material, relationships were derived for the size of riprap lining necessary to provide an erosion-resistant surface.

For the purposes of such design the following conditions were assumed to apply:

1. The drainage channel will be essentially straight.

2. The flow will be essentially uniform and can be described by the Manning formula:

\[ v = \frac{1.49}{n} R^{2/3} S_b^{1/2} \]  

in which \( v \) is the mean velocity, \( n \) is the roughness coefficient, \( R \) denotes the hydraulic radius, and \( S_b \) represents the longitudinal bed slope.

3. The roughness coefficient will depend on the effective size of the riprap and can be expressed as

\[ n = 0.04 d_{50}^{1/6} \]  

in which \( d_{50} \) represents the particle size than which 50 percent is finer by weight.

4. The critical boundary shear stress is directly proportional to the effective size of the riprap and can be expressed as

\[ \tau_c = 4d_{50} \]  

5. The ratio of the maximum shear stress to the mean shear stress is taken to be 1.5 for trapezoidal channels and 2 for wide triangular channels with very mild side slopes; that is,

\[ \tau_{c(max)} = 1.5 \gamma R S_b \]  (trapezoidal)  

\[ \tau_{c(max)} = 2 \gamma R S_b \]  (triangular)
and

\[ \tau_{o(\text{max})} = 2 \gamma R S_b \quad \text{(triangular)} \]  

(5)

For regular trapezoidal channels these assumptions give rise to the following equations relating the discharge, velocity, and hydraulic radius to the longitudinal slope, the size of the riprap, and the shape of the channel:

\[ Q = \frac{1}{118} \frac{d_50^{5/2}}{S_b^{13/6}} \frac{P}{R} \]  

(6)

\[ V = 4.60 \frac{d_{20}^{1/2}}{S_b^{1/6}} \]  

(7)

and

\[ R = 0.0428 \frac{d_{20}}{S_b} \]  

(8)

Eq. 6 shows that for a given discharge and slope the minimum size of riprap needed to protect the channel depends only on the channel's shape as prescribed by \( P/R \). Once the size of riprap is determined, the velocity and hydraulic radius can be computed from Eqs. 7 and 8. From these two equations and the discharge, the required cross-sectional area and wetted perimeter can be obtained. These, in turn, provide the basis for computing the bottom width of the channel and the water depth. To facilitate such computations a set of charts prepared for the original report is included here for reference. Figures 2 and 3 represent Eq. 6 for \( P/R = 13.3 \) and \( P/R = 30 \), respectively. These values of \( P/R \) represent the range of channel shapes likely to be encountered. The smaller value represents a relatively deep and narrow channel; the larger, a wide and relatively shallow channel. The respective values of riprap size obtained from these two figures represent the maximum and minimum sizes that will be just stable in their respective channels. Any intermediate size would result in an intermediate value of \( P/R \), and hence an intermediate channel shape. Once the size of riprap is chosen, the velocity and hydraulic radius are determined from Figures 4 and 5 and the cross-sectional area is obtained from Figure 6. The side slope required for stability is then obtained from Figures 7 and 8. By use of this side slope and the calculated cross-sectional area and hydraulic radius, the channel geometry can be obtained directly from the appropriate section of Figure 9. In these design charts the side slope is established so that the riprap on the side is as stable as that on the bottom, which in turn is the minimum size that will be stable for the given discharge and channel slope.

For triangular channels, which for safety reasons are often necessary in median strips, the calculations are somewhat simpler because the shape of the triangular channel represented by \( P/R \) depends only on the side slope. In addition, the riprap size needed for such channels would usually be somewhat smaller than that necessary for larger trapezoidal channels. To simplify the design and construction of linings for small
Figure 2. Minimum size (mean) of stone riprap that will be stable in trapezoidal channels with $P/R = 13.3$ for various combinations of discharge and slope (Fig. 19).
Figure 3. Minimum size (mean) of stone riprap that will be stable in trapezoidal channels with $P/R = 30$ for various combinations of discharge and slope (1, Fig. 20).

$\gamma_s = 165 \text{pcf}$

$\frac{P}{R} = 30$
Figure 4. Maximum mean velocity for stable riprap in trapezoidal channels for various mean stone sizes and shapes (I, Fig. 21).
Figure 5. Hydraulic radius for trapezoidal channels in terms of mean stone size and slope (I, Fig. 22).
Figure 6. Area of a trapezoidal channel in terms of discharge and maximum mean velocity (I, Fig. 23).
Figure 7. Angle of repose of riprap in terms of mean size and shape of stone (1, Fig. 24).

Figure 8. Recommended side slopes of trapezoidal channels in terms of riprap angle of repose (1, Fig. 25).
Figure 9a. Geometry of trapezoidal channels with 1.5:1 side slopes (Fig. 26a).
Figure 9b. Geometry of trapezoidal channels with 2:1 side slopes (1, Fig. 26b).
Figure 9c. Geometry of trapezoidal channels with 2.5:1 side slopes (Fig. 26c).
Figure 9d. Geometry of trapezoidal channels with 3:1 side slopes (Fig. 26d).
Figure 9e. Geometry of trapezoidal channels with 4:1 side slopes (1, Fig. 26e).
channels, the riprap sizes were chosen from standard sizes of coarse aggregate such as those listed in AASHO designation M43-54, "Standard Sizes of Coarse Aggregate for Highway Construction." The gradations of eight of these standard sizes having a reasonably systematic change in mean diameter are given in Table 1. It is thought that local aggregates having

Table 1. SIZES AND MEAN DIAMETERS OF COARSE AGGREGATES*

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>No. 1</th>
<th>No. 2</th>
<th>No. 24</th>
<th>No. 4</th>
<th>No. 357</th>
<th>No. 467</th>
<th>No. 57</th>
<th>No. 68</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 In.</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 1/2 In.</td>
<td>90-100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 In.</td>
<td></td>
<td>100</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 1/2 In.</td>
<td>25-60</td>
<td>90-100</td>
<td>90-100</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 In.</td>
<td>35-70</td>
<td>100</td>
<td>95-100</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 1/2 In.</td>
<td>0-15</td>
<td>0-15</td>
<td>25-60</td>
<td>90-100</td>
<td>95-100</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 In.</td>
<td></td>
<td>20-55</td>
<td>35-70</td>
<td>95-100</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/4 In.</td>
<td>0-5</td>
<td>0-10</td>
<td>0-15</td>
<td>35-70</td>
<td>90-100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/2 In.</td>
<td></td>
<td>0-5</td>
<td>10-30</td>
<td>25-60</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/8 In.</td>
<td>0-5</td>
<td>0-5</td>
<td>10-30</td>
<td>30-65</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 4</td>
<td>0-5</td>
<td>0-5</td>
<td>0-10</td>
<td>5-25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 8</td>
<td>0-5</td>
<td>0-5</td>
<td>0-10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 16</td>
<td>0-5</td>
<td>0-5</td>
<td>0-5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[d_{50} \, (b)\] 0.185 0.149 0.109 0.080 0.059 0.044 0.034 0.024

(a) Adapted from AASHO Standard Specification M43-54.

(b) Mean particle size diameter (in feet) at which 50 percent is finer by weight.

*Table 1 from NCHRP Report 108.
approximately the same gradation and mean diameter could be used. The equation relating the discharge size, longitudinal slope, and side slopes can then be written as

\[ Q = \frac{1}{64.4} \frac{d_{50}^{1/2} z^2 + 1}{S_b^{13/6} z} \]  

(9)

in which \( Z \) is the side slope, and the depth, \( y \), is obtained from

\[ y = 0.064 \frac{d_{50}}{S_b} \frac{(Z^2 + 1)^{1/2}}{Z} \]  

(10)

Inasmuch as the depth of flow is also a function of the side slope, it can be determined directly from Eq. 10 once the side slope has been established. This has been done in Figures 10 through 17, from which the size of riprap and the depth of flow can be determined for any given discharge, longitudinal slope, and side slope.
Figure 10. Depth of flow and size of standard aggregate for channel stability

Triangular channel
Side slope 3:1

(1, Fig. 27).
Figure 11. Depth of flow and size of standard aggregate for channel stability

Triangular channel
Side slope 4:1

(1, Fig. 28).
Figure 12. Depth of flow and size of standard aggregate for channel stability

Triangular channel
Side slope 5:1

(1, Fig. 29).
Figure 13. Depth of flow and size of standard aggregate for channel stability

Triangular channel
Side slope 6:1

(1, Fig. 30).
Figure 14. Depth of flow and size of standard aggregate for channel stability

Triangular channel
Side slope 7:1

(1, Fig. 31).
Figure 15. Depth of flow and size of standard aggregate for channel stability

Triangular channel
Side slope 8:1

(1, Fig. 32).
Figure 16. Depth of flow and size of standard aggregate for channel stability

Triangular channel
Side slope 9:1

(1, Fig. 33).
Figure 17. Depth of flow and size of standard aggregate for channel stability

Triangular channel
Side slope 10:1

(1, Fig. 34).
Chapter 2. FINDINGS

The drainage channels that have been designed and constructed in accordance with these design procedures and are available for preliminary evaluation are listed in Table 2 and described in detail in the appendices. All the channels so far constructed are in good condition; however, only two channels have experienced a discharge approaching the design discharge.

Hop Brook, a channel relocation, is located in Manchester, Conn. Figure 18 is a general view of the channel after two years of use. Vegetation has covered the side slopes above the riprap, and in many spots grass is growing among the rocks in the lower portion of the channel. Hop Brook's design discharge was 3,900 cfs, but the maximum discharge that has been experienced to the present time is estimated to be only 1,500 cfs. The only evidence of stress beyond the channel's capacity was localized at the side inlets, where the excess energy of the flow from the inlet could not be appropriately dissipated. This situation was easily taken care of during maintenance operations.

A section of a drainage channel near Moose Lake, Minn., after one year of operation is shown in Figure 19. Since its construction the channel sides above the riprap and the highway shoulder have been completely covered with grass, some of which is encroaching on the riprap. The drainage channel, which was designed for 275 cfs, has been subjected to a flow near the design capacity as a result of unusually heavy rainstorms in the area. Debris and logs on the side slope strongly suggest that the depth during the recent flood was of the order of 3 ft. The riprap specified for this channel had a 50 percent size of 0.25 ft. The inspection indicated that the channel effectively withstood the attack of the flood flow. The channel was in good condition with little or no movement of the riprap on the sides or the bottom. A sample of the riprap material indicated that the mean size of the rock was nearly equal to that specified.

The roadside ditch in Chippewa County, Wis. (Figure 20) was found to be in surprisingly good condition after three years of operation. The only damage to the ditch appeared to have been done by maintenance vehicles driving over the loose rock during the mowing operation. Estimates of the maximum flow to which the ditch had been subjected were made on the basis of high-water marks found in the depth gauges, which indicated that the design depth of about 0.5 ft had been reached. Other high-water marks indicated a depth of 0.25 ft or less.

The median drainage ditch on a divided Interstate highway near Billings, Mont. is shown in Figure 21. The slope of this channel is somewhat greater than that covered by the design charts for triangular channels, but the rock riprap could be proportioned using Eq. 9. It has successfully withstood one hydrologic event approximating the design discharge which caused failure of a blanket-type lining used on a nearby channel. The blanket has since been replaced by riprap.

So far, none of the channels has failed. Although only two appear to have been subjected to the design discharge, no damage has been observed in the channel proper. Evidence indicates that special protection is needed at the outlets of structures such as culverts. For the channel at Moose
Table 2. DRAINAGE CHANNELS DESIGNED ACCORDING TO PROPOSED TENTATIVE DESIGN PROCEDURES

<table>
<thead>
<tr>
<th>Location</th>
<th>Present State</th>
<th>Design Q (cfs)</th>
<th>Design Slope</th>
<th>d&lt;sub&gt;50&lt;/sub&gt; (ft)</th>
<th>Bottom Width (ft)</th>
<th>Side Slopes</th>
<th>Design Depth (ft)</th>
<th>Max. Q to date (cfs)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Present Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manchester, Conn.</td>
<td>Const. 1969</td>
<td>3900</td>
<td>0.007</td>
<td>1.06</td>
<td>1.5</td>
<td>20</td>
<td>2:1</td>
<td>9.15</td>
<td>1500 Very good, vegetation on sides and top. Mean size of riprap appears to vary somewhat along channel.</td>
</tr>
<tr>
<td>Moose Lake, Minn.</td>
<td>Const. 1971</td>
<td>275</td>
<td>0.003</td>
<td>0.21</td>
<td>0.25</td>
<td>12</td>
<td>3:1</td>
<td>4.0</td>
<td>250 Channel very good. All riprap in place. Erosion at outlet of culvert at upstream end.</td>
</tr>
<tr>
<td>Klamath Falls, Ore.</td>
<td>Design 1971</td>
<td>1100</td>
<td>0.0054</td>
<td>0.43</td>
<td>15</td>
<td>2.5:1</td>
<td>5.3</td>
<td>-</td>
<td>Chandler Wayside Park</td>
</tr>
<tr>
<td>Chippewa County, Wis.</td>
<td>Const. 1969</td>
<td>6</td>
<td>0.017</td>
<td>0.08</td>
<td>0.08</td>
<td>10</td>
<td>4:1</td>
<td>0.5</td>
<td>- Roadside drainage. Good condition. Some damage from truck wheels.</td>
</tr>
<tr>
<td>Montana I-90-8(66)</td>
<td>Const. 1971</td>
<td>18</td>
<td>0.05</td>
<td>0.6</td>
<td>0.33</td>
<td>0</td>
<td>6:1</td>
<td>-</td>
<td>- Median strip appears to be in good condition. Riprap gravel, uniformly graded 2-in. minimum to 8-in. maximum.</td>
</tr>
</tbody>
</table>

<sup>a</sup>Approximate
Figure 18. Hop Brook channel, Manchester, Conn., looking downstream.

Figure 19. Moose Lake, Minn., channel looking upstream.
Figure 20. Roadside channel near Chippewa Falls, Wis.

Figure 21. Median drainage ditch near Billings, Mont.
Lake, Minn., the region around the wingwalls of the culvert was not ade-
quately protected; therefore, vortices generated at the culvert outlet and
other secondary currents have removed a considerable amount of earth mate-
rial from behind the wingwalls and widened the channel immediately down-
stream of the culvert.
Chapter 3. INTERPRETATIONS

Within the limits fixed by the relatively few channels on which observations could be made, the design procedures outlined in the previous report (1) appear to be appropriate and useful for the design of riprap-lined channels. Those channels for which they had been used appeared to be quite stable and effective in transporting surface runoff in connection with highway development. Although only two channels have been tested at discharges approximating their design floods, their stability lends confidence to the use of these procedures. In the development of the design charts and equations, conservative values of the constants were chosen, and only by observing the channels in use can it be determined whether these constants were unduly conservative. An additional factor of safety is introduced by the fact that riprap for a particular application is usually chosen from among standard riprap gradations and the next larger size to that indicated is applied. It is almost always more economical to specify a standard gradation for riprap than to develop a gradation specifically for a particular channel. For this reason, the riprap size is almost always larger than that specified by the design charts. The only effect of using riprap larger than that specified by the charts is a minor increase in the relative roughness of the channel due to the larger particles. In most cases this small increase in relative roughness is negligible.

In all cases in which the riprap lining is a year or more old, grass has grown on the slope above the riprap and through the interstices of the rock. In some cases the rock is no longer visible. The vegetation greatly improves the appearance of the channel. The grass growing up through the rock interstices also provides added protection by increasing the resistance of the riprap to incipient movement. If it is certain that vegetation will grow among the particles, it may be possible to reduce the size of the riprap. In any case, the vegetation does make the design somewhat more conservative. A secondary effect of the vegetation is a reduction in the channel roughness coefficient; the grass is bent over by the flow and thus presents a smoother surface than the bare rock.

Subsidiary benefits of riprap linings are their simplicity of design, the relative ease of construction, and the reduced cost if suitable riprap is available in the area. Estimates of the cost of the lining for the Manchester, Conn., stream relocation showed a saving of $94,000 compared to an equivalent paved lining. In general, the amount of saving will depend on the situation, particularly the availability of appropriate riprap.

In addition to the cost savings they make possible, the procedures lend themselves to adaptation by various design agencies. The Kansas Highway Department has used the design procedures to establish specifications for a series of predesigned channels all having side slopes of 4:1, but of varying bottom widths to accommodate a range of discharges and longitudinal slopes (2). The Minnesota Highway Department has combined the riprap lining with topsoil to support the growth of grass. As the vegetation develops, the root structure penetrating the rock interstices provides a significant increase in the resistance of the system to erosion or removal. In addition, the vegetation improves the appearance of the drainage system (2).
Chapter 4. RECOMMENDATIONS FOR FURTHER STUDY

Continued Field Evaluation

It can be concluded that a definitive test of the design procedures will require more field data from more channels, particularly in arid areas, and more time for the occurrence of design discharges in the various channels. Because of imminent termination of the present project, it is recommended that an ongoing program of field observations be undertaken by a permanent highway organization that is concerned with the continued upgrading of highway design practices. As more observations become available, the design charts can be adjusted in the direction of either conservatism or liberalization to reflect the modifications suggested by field studies.

For such future evaluations it would be most appropriate for channels to be designed and constructed in the course of regular highway development programs. After a year or more of operation, a channel's effectiveness in conveying runoff water can be evaluated. Provisions should be made for measuring or estimating the discharge and depth in the channel. After a significant flood the depth of flow can be determined from the elevation to which debris has been deposited on the channel sides. Useful data can be collected and noted on a form such as that shown in Figure 1.

Culvert Outlets

Inspections of the study drainage channels indicated that special care must be taken with regard to culverts and other transition structures leading into drainage channels. Such structures cause localized increases in velocity and scouring forces that are not accounted for in the design procedures. These increased scouring forces must be counteracted by the placement of appropriately larger sizes of riprap. The choice of the larger sizes must be based on a separate study of culvert hydraulics; this is beyond the scope of the present study.
REFERENCES


The highway through the urban area of Manchester, Conn., was constructed in the valley of Hop Brook. The valley floor is flat, the flood plain varying in width from 200 to 400 ft with a general slope of approximately 0.007 ft/ft in the reach affected by the highway. The stream channel proper was meandering and of relatively low capacity. Overbank flow occurred frequently, and the floodplain supported a heavy growth of brush. The relocated channel is 4,400 ft long and replaces the over-5,500-ft (low-water channel length) original stream. The design discharge for this channel is 3,900 cfs, or five times the computed mean annual flood of 780 cfs.

The channel selected for this relocation had a bed width of 20 ft and 2:1 side slopes. The mean stone size for the riprap was somewhat over 1.5 ft and was based on the Connecticut Standard Material Specification, which says, in part, "...all stones shall weigh not less than 20 pounds nor more than 1,000 pounds and at least 75 percent of the mass shall be stones weighing more than 150 pounds. No dimension shall be less than 6 inches."

The discharge of the channel (3,900 cfs) is larger than the maximum value of the design charts given in NCHRP Report 108 (1) and incorporated in this report, so that the design is more easily accomplished by using the design equations (Eqs. 6, 7, and 8). Using Eq. 6 and assuming

\[ \frac{P}{R} = 13.3 \text{ as given in Figure 2, } d_{50} = \left( \frac{118 Q S_{b} \sqrt{d_{50}}}{P/R} \right)^{2/5} = 0.88 \text{ ft} = 268 \text{ mm.} \]

Figure 7 shows that for crushed rock 268 mm in size, the angle of repose is about 42\(^\circ\), so that according to Figure 8 the side slopes, \( \phi \), should be 2.5:1. Therefore, from Eq. 8, \( R = 0.0428 \frac{d_{50}}{S_{b}} = 5.38 \text{ ft;} \)

from Eq. 7,

\[ V = 4.60 \frac{d_{50} \sqrt{d_{50}}}{S_{b}^{1/6}} = 9.85 \text{ fps;} \]

and so

\[ A = Q/V = 396 \text{ sq ft.} \]

Then, for 2.5:1 side slopes,

\[ A = 396 = by + 2.5 y^{2} \]

and

\[ P = A/R = 73.7 = b + 2\sqrt{7.25} y \]

from which \( y = 7.7 \text{ ft and } b = 32.2 \text{ ft.} \) A riprap-lined channel of these dimensions \( (y = 7.7 \text{ ft, } b = 32.2 \text{ ft, } d_{50} = 0.88 \text{ ft, and } P/R = 13.3) \) would be a stable channel, but the bottom width is considerably larger than that used in the prototype. On the other hand, if the channel bottom width were reduced to zero, the channel would be triangular in shape and
From this it is deduced that \( P/R \) for the 20-ft bottom-width prototype channel lies between 11.6 and 13.3. After some trials it is assumed that \( P/R = 11.9 \).

Then, by Eq. 6, 
\[
d_{50} = \left( \frac{11.8 Q S_b^{13/6}}{11.9} \right)^{2/5} = 0.92 \text{ ft} = 280 \text{ mm};
\]

by Eq. 8, 
\[
R = 0.0428 \frac{d_{50}}{S_b} = 5.63 \text{ ft};
\]

by Eq. 7, 
\[
V = 4.60 \frac{d_{50}^{1/2}}{S_b^{1/6}} = 10.0 \text{ fps};
\]

so \( A = Q/V = 390 \text{ sq ft} \), and 
\[
P = A/R = 69.3 \text{ ft}. \]

The channel shape is computed from

\[
A = 390 = b y + 2.5 y^2
\]

and

\[
P = 69.3 = b + 2\sqrt{7.25 y}
\]

from which \( y = 9.15 \text{ ft} \) and \( b = 20.0 \text{ ft} \).

From these computations a riprap-lined channel having a 20-ft bottom width and 2.5:1 side slopes, using a riprap of 0.92-ft size, would be stable and would have a flow depth of 9.15 ft. The prototype channel, however, was constructed with 2:1 side slopes. Steeper side slopes necessitate somewhat larger riprap for stability. The increase is given by Eq. 33 of NCHRP Report 108 (1), in which \( K \) and \( K' \) are the ratios of critical shear on the side slope to that on the bed for side slopes of 2.5:1 and 2:1, respectively. These values can be obtained from Figure 15 of the same report, in which \( K = 0.84 \) and \( K' = 0.73 \). Substituting these values in Eq. 33, the riprap size for the steeper side slopes is \( d_{50}' = 1.06 \text{ ft} = 320 \text{ mm} \). That is, a channel with a bottom width of 20 ft and 2:1 side slopes would be stable if riprap with \( d_{50} = 1.06 \text{ ft} \) were used for the lining. Inasmuch as riprap with \( d_{50} = 1.5 \) was used for the channel lining, it should be quite stable for the design discharge.

Inspection of the channel after approximately three years showed it to be in very good condition and the riprap to be relatively undisturbed. Figure A-1 shows a reach of the channel upstream of one of the control structures installed for energy dissipation. The riprap appears to be uniform in composition throughout this reach, and it has been carefully placed. In the construction phase the "preliminary excavation was done by hauling scrapers and bulldozers, leaving only a minor amount of finish grading to be accomplished. A G-1000 Gradall was set in the channel, starting at the downstream end. The finish excavation was shaped by the Gradall and the riprap delivered into the channel bottom by dump semi-trailers. The
Figure A-1. Section of Hop Brook channel with uniformly placed riprap.

Figure A-2. Another section of channel with less uniform riprap.
Gradall placed the riprap on the bed and banks to the finish template within very close tolerances." (4)

Since the initial construction period, grass and some shrubbery have grown up among the rocks and above the riprap on the side slopes. With the passage of time the rock may be hidden by the vegetation, with a consequent improvement in appearance. Unless the vegetation is very thick, its presence will tend to reduce the channel roughness and hence the depth of flow.

It has been estimated that the maximum discharge to which the channel has been subjected is approximately 1,500 cfs; thus, damage would not ordinarily be expected. The riprap in the section of the channel shown in Figure A-1 is uniformly placed. It is not known whether the branch in the figure was deposited by the flow. Figure A-2 shows another section of the channel in which the riprap is not as uniform in size or placement. Grass and shrubs have grown up among the rocks, and the surface is not as smooth as in the previous case.

The riprap on the bed of the channel has been covered with sand and fine gravel; thus, the rocks making up the riprap are not visible in this area. The sand and gravel are now being transported over a relatively smooth surface.

Figures A-3 and A-4 show drain outlets that discharge into the main channel. Both outlets are protected by rock from the erosive force of the water discharging from them. Figure A-3 shows that the appearance of the channel can be enhanced if trees located on the banks out of the flow area are left in place. Figure A-4 shows clearly a section of the channel where the riprap is considerably smaller—and will probably be less effective in resisting a design flood—than that in the previous figures. It is apparent that the trees planted along the bank will improve the appearance of the site.

With regard to specific costs, the following was communicated to the principal investigator:

Use of riprap in a blanket 2 ft thick requires approximately 1.2 ton per square yard. The Contractor's bid price on this contract is $4.75 per ton. Approximately 9-1/2 tons are required per foot of channel, making the cost per foot of channel lining to be $45.00.

Job cost for the riprap is estimated at $183,000 as compared to $277,000 for the paved lining. The cost of the energy dissipation structures has not been estimated. (4)
Figure A-3. General view of Hop Brook channel and surroundings.

Figure A-4. Drain outlet protected by rock.
Appendix B. MOOSE LAKE, MINNESOTA, CHANNEL

At Moose Lake, Minn., a prototype drainage channel planned for erosion control and stream relocation was constructed between a railroad embankment and a highway as part of the drainage system for the highway. It was deemed necessary to relocate the existing channel to avoid probable flood damage to nearby residences. The new channel has reduced the length of the natural channel and thereby increased the slope to the extent that a drop structure is required at the end of a 10x4-ft box culvert under a highway at the upstream end of the channel. In addition to the riprap-lined channel, the plans included a 10-ft berm on the side of the railroad embankment. For this application a design flow of 275 cfs was to be conveyed through a channel with a slope of 0.03 ft/ft. The channel as constructed had a 12-ft bottom width with 3:1 side slopes and was lined with rounded gravel aggregate having a mean size, $d_{50}$, of 0.25 ft and the following gradation: passing 4 in., 90 to 100 percent by weight; passing 3 in., 20 to 60 percent; and passing 2 in., 0 to 15 percent.

For this discharge and slope the figures can be used directly to determine an appropriate channel geometry and riprap size. For $P/R = 13.3$, from Figure 2, $d_{50} = 0.15$ ft; from Figure 4, $V = 4.6$ ft; from Figure 5, $R = 2.1$ ft; from Figure 6, $A = 60.0$ ft; from Figure 7, $\Theta = 35.4^\circ$ (well-rounded gravel); from Figure 8, $\phi = 3:1$ side slopes; and from Figure 9d, $b = 0.0$ and $y = 4.5$ ft. These results show that the computed channel would be triangular in cross section. In fact, $P/R = 13.3$ is the minimum value for a trapezoidal channel with 3:1 side slopes. In the same way, Figure 3 for $P/R = 30$ would result in a wider channel and a somewhat smaller riprap size. Therefore, through several trials using successively smaller values of $d_{50}$ with either the charts or the relevant equations, the geometry of an appropriate channel can be developed. It is found that for $d_{50} = 0.14$ ft, $R = 2.0$ ft, $V = 4.52$ ft, $A = 60.9$ sq ft, $P = 30.45$ ft, $y = 2.95$ ft, and $b = 11.85$ ft.

This channel, having a bottom width of approximately 12 ft and 3:1 side slopes, corresponds to the prototype as constructed. These computations show that the channel would be stable if lined with riprap whose $d_{50}$ was only 0.14 ft, or 1.68 in. In the prototype, however, the riprap was a well-rounded gravel of mean size $d_{50} = 0.25$ ft. It can be concluded, therefore, that the prototype channel constituting the relocated stream will be stable for the design flow.

The general appearance of the channel and its riprap is shown in Figure 19; Figure B-1 is a close-up of the riprap prior to its being subjected to flow. The mean size, $d_{50}$, is 0.25, and the photo shows that the rounded gravel was relatively uniformly laid in this area. In other areas the riprap was not as smoothly graded or as uniformly thick. An analysis of a sample of the rock taken from the channel is shown in Figure B-3, together with a plot of the specified gradation. This sample agrees well with that specified and shows that the mean size of the gravel was 65 mm, or 0.21 ft.
Figure B-1. Riprap for Moose Lake, Minn., channel, $d_{50} = 0.25$ ft.

Figure B-2. Moose Lake channel one year after construction following design flood.
Figure B-3. Size distribution of riprap, Moose Lake channel.
Figure B-4. Another view following flood--logs indicate maximum flood stage.

Figure B-5. Channel filled with early spring runoff.
In the spring of 1972 heavy rainstorms in the locality of the channel provided a discharge approximately equal to the design value. That the depth approximated the design value can be seen in Figures B-2 and B-4. Figure B-2, taken one year after construction, shows that the side slopes above the riprap were covered with grass from an elevation about 3 ft above the channel bed and that grass was also beginning to grow in the interstices between the rocks. Grass and twigs have been deposited by the flood on the side slope at the top of the riprap covering and at an elevation about 3 ft above the channel bed, but the riprap does not appear to have been disturbed. Figure B-4 is a similar view of the undisturbed riprap and the encroaching vegetation. Two small logs deposited on the bank by the flow are visible. Their location is a measure of the maximum stage of the flood.

Figure B-5 shows the channel in flood as a result of early spring runoff. The discharge is somewhat less than the design discharge, but the stage is maintained by the backwater effect of the river into which the drainage channel discharges. The stage is slightly above the riprap on the near side, but not on the far side, where some of the riprap still shows above the water surface. The backwater effect has also reduced the velocity of the water below normal. A rather large volume of ice is attached to the bottom of the channel, forcing the water to flow over the ice. This tends to reduce the cross-sectional area and raise the surface elevation of the water.

Inspection of the Moose Lake, Minn., riprap-lined channel indicates that it is stable and is functioning as expected.
Near Klamath Falls, Ore., Crooked Creek flows through the Chandler Wayside Park. It is proposed to run a channel adjacent and parallel to the existing highway to accommodate the peak discharges. The creek will pass through existing double 10x7-ft reinforced concrete culverts at each end of the channel change. The design discharge of 1,100 cfs (50-year frequency) will be conveyed through a riprap-lined channel whose slope is 0.0054 ft/ft. For this discharge and slope an appropriate channel would have a bottom width of 15 ft, 2.5:1 side slopes, and a depth of 5.3 ft and be lined with riprap whose mean size \( d_{50} \) was 0.43 ft. Because the proposed channel would be parallel to and adjacent to the roadway, side slopes of 1.5:1 were chosen to reduce the over-all width. This required that the size of the riprap (Eq. 33) be increased to 0.75 ft (9 in.).

Construction of the channel at Klamath Falls is being held in abeyance to permit further development of the park area and consideration of a possible realignment of the channel itself. Figure C-1 shows the originally proposed alignment adjacent to the state highway. The proposed channel would divert floods from the park site. The park area through which the present Crooked Creek flows is shown in Figures C-2 through C-4. Crooked Creek meanders through the area during low flow, but is also subject to floods that inundate the floodplain and cause excessive bank erosion in the bends. Figure C-2 shows a portion of Crooked Creek within the park. During floods the floodplain, on which campsites will be located, will be inundated. Figure C-3 shows the bank erosion that occurs in the creek bends within the park area when there is a flood. In Figure C-4 the double 10x7-ft reinforced concrete box culvert through which Crooked Creek leaves the park area can be seen.
Figure C-1. Proposed alignment of Crooked Creek next to highway.

Figure C-2. Present Crooked Creek in Chandler Wayside Park.
Figure C-4. Culvert through which Crooked Creek leaves park.

Figure C-3. Bank eroded by flooding.
Appendix D. CHIPEWA COUNTY, WISCONSIN, CHANNEL

In Chippewa County, Wis., a section of a drainage channel adjacent to a highway was being eroded. It was repaired and riprapped to prevent further erosion from occurring. In this particular application the analysis included determination of the peak runoff from the surrounding drainage area, 14.4 acres consisting of 95 percent pasture and 5 percent woods. The watershed slope varied from 2 to 10 percent. The 25-year discharge was 25 cfs, but the design discharge was greatly reduced to correspond to a somewhat higher frequency. For purposes of design the discharge was established at 6 cfs and the slope at 0.017 ft/ft. Because the channel is adjacent to the highway and provides ordinary drainage, it should be relatively wide and shallow. A channel of trapezoidal cross section having a 10-ft bottom width and 4:1 side slopes was chosen. By application of the equations previously outlined, the flow depth would be 0.22 ft and the riprap would have a \( d_{50} \) size of approximately 0.08 ft. This corresponds to No. 4 riprap, based on AASHO Standard Specification M43-54. Because the laboratory experiments made in connection with the development of the procedures indicated that only insignificant amounts of riprap would be moved at discharges considerably in excess of the design discharge, the designers felt that the channel should be relatively safe for discharges of approximately 10 cfs.

The evolution of the riprapped drainage channel is shown in Figures D-1 through D-3. Figure D-1 shows significant erosion in the steeper portion of the side drainage channel \( (S = 0.017) \); in the flatter portions of the ditch the grass cover was sufficient to protect the underlying soil. Figure D-2 shows part of the construction process in which, following grading, a gravel having a mean size \( d_{50} \) of 0.08 ft is being placed along the channel. Figure D-3 shows the channel after one year of operation. The riprap appears to be well settled, and grass is beginning to appear among the rocks. Approximately three years after construction, as shown in Figure D-4, more vegetation has been established in the channel. During this period it has been subjected to one flow for which the discharge equaled or exceeded the design discharge.

The riprap-lined channel is approximately four years old. As Figure D-4 shows, "the ditch is in surprisingly good condition. The only damage to the ditch appeared to have been made by maintenance vehicles driving over the loose rock during moving operations."
Figure D-1. Chippewa County, Wis., drainage channel prior to riprapping.

Figure D-2. Gravel being placed along the channel.
Figure D-3. Channel approximately one year after construction.

Figure D-4. Channel approximately three years after construction.
Appendix E. BILLINGS, MONTANA, CHANNEL

A riprap-lined drainage channel located about 15 miles southeast of Billings, Mont., on I-90 serves to drain the median strip of the divided highway. The maximum contributary area is not greater than 4 acres, from which a discharge of 6.5 cfs occurs once in two years and a discharge of 18 cfs once in ten years. The slope of the median ditch is 0.05 ft/ft. The design for median ditches calls for a triangular cross section with 6:1 side slopes. Because the slope exceeds the range covered by Figure 13 for 6:1 side slopes, the properties of the channel must be determined from Eq. 9, which was used to construct the charts. The riprap size can be determined from Eq. 9, inasmuch as all the other variables are given, as well as the depth, y (from Eq. 10), after the riprap size has been computed. From these values the velocity and the hydraulic radius can be computed. These computations give the following results for the conveyance of an assumed maximum flow of 18 cfs in a riprap-lined triangular channel with 6:1 side slopes and a slope of 0.05 ft/ft: \( d_{50} = 0.603 \text{ ft} = 7.25 \text{ in.} \); \( y = 0.785 \text{ ft} \); \( V = 4.85 \text{ fps} \); and \( R = 0.386 \text{ ft} \).

In the construction of the channel, however, a uniformly graded gravel having a maximum size of 8 in., a minimum size of 2 in., and a \( d_{50} \) size of 4 in. was specified. Using such gravel, the design discharge becomes about 4 cfs (Eq. 9). Because the experiments related to this design showed that the transport of the riprap was negligible at discharges less than twice the design discharge, it can be concluded that the channel will be essentially stable for discharges less than 8 cfs.

Figures E-1 through E-4 show various aspects of the channel draining the median strip of the highway and its riprap lining. Figure E-1 shows the rather steep slope of the channel, which necessitated relatively large riprap. Some vegetation is beginning to grow among the rocks. Figure E-2 is a closer view of the channel showing the alignment, the flat side slopes, and vegetation along the sides. Figure E-3 is a close-up of the rounded gravel particles being used for riprap. The gravel size ranged from a maximum of 8 in. to a minimum of 2 in. Vegetation is growing through the interstices. Figure E-4 shows the erosion taking place in a nearby side ditch that leads to a corrugated metal drain on a much steeper slope. This unprotected channel has been eroded to a depth of about 2 ft.
Figure E-1. Overall view of drainage channel and surroundings looking downstream.

Figure E-2. Closer view of channel.
Figure E-3. Close-up of rounded gravel used for riprap.

Figure E-4. A nearby unprotected channel.