The Design of Low Water Stream Crossings

STANLEY L. RING

When a bridge becomes obsolete, and the road must remain open to traffic, perhaps at a new location, a low-cost alternative may be to replace it with a low water stream crossing. A low water stream crossing consists of a series of culverts that are deliberately designed so that the crossing is at a low grade and stream flow at high water frequently overtops the grade. A design manual for low water stream crossings was prepared for the Iowa Highway Research Board. A description is provided of the major steps and considerations in the design of a low water stream crossing. The decision to build a low water stream crossing is based on the road classification. A primitive road is an excellent candidate. The first step is to select the frequency of overtopping that can be tolerated and then calculate a discharge Q_e. A series of pipes are selected with this overtopping discharge value in mind to minimize the roadway fill over the stream. The design procedures offer criteria for the grade line design and for the final cross-section of the roadway. General construction details and guidelines for the selection of materials and final signing are also presented.

A low water stream crossing (LWSC) is a street or road that crosses a stream; the flow of storm water in the stream periodically overtops the roadway. The roadway may frequently be flooded, in which case the road must be closed to vehicular traffic during the higher stages of stream flow. Low water stream crossings are grouped into two main types in this discussion: unvented fords and vented fords.

An unvented ford is a roadway that crosses the stream without the use of any pipes (culverts). Low flows in the stream may pond and flow over the roadway if the stream flow is intermittent, or low flows may overtop the roadway most of the time. The early settlers of this nation located trails so that they would be able to cross streams at points where the streambed was hard and the water depth during relatively dry periods allowed for the passage of vehicles. A roadway can be built above minor streams except a channel must be provided near the center. On larger streams the ford may only consist of approach ramps that lead to a relatively stable stream bed.

A vented ford consists of a cross-section for the roadway above the stream bed, and a pipe or number of pipes under the roadway that will provide for low water stream flows without overtopping the roadway. High water will periodically flow over the roadway because the pipes are deliberately sized to be too small for all but the smallest flows.

Another type of LWSC is a low water bridge. A low water bridge is a flat-slab bridge deck at about the elevation of the adjacent stream banks, with a smooth cross-section that is designed in such a manner that high water will flow over the slab without damaging the slab bridge; when the water recedes, the bridge can be used immediately.

GENERAL APPLICATIONS

An unvented ford is primitive. If the stream has a continuous flow of water, normal automobile traffic may encounter operational problems at the wet crossing. Four-wheel-drive and farm vehicles may not encounter problems, except during high water flows. Specialized access roads may consequently have to be built that are suitable for unvented fords. The unvented ford also requires considerable maintenance. Limited design criteria are available for this road type. The only application for unvented fords often is at intermittent streams that are dry for a significant portion of the year.

The vented ford LWSC, however, has numerous applications because the design can limit the flow over the roadway to a very few days of the year. If the closing of the road for short periods of time can be tolerated, the LWSC may offer significant savings over a culvert with a roadway fill designed to provide for a 25- or 50-yr discharge without overtopping.

A primitive road that serves only as a field access for local farmers is a classic example of an LWSC candidate. During good weather conditions, a well-designed vented ford can perform adequately for any traffic using the road. In fact, an LWSC might be superior to the typical obsolete bridge found at this site. This type of bridge might be a wooden structure that was built on a narrow roadway just after the turn of the century. Farmers using modern farm equipment even have problems with modern bridges. Bridges were not designed for farm equipment that commonly reach widths of 18 to 20 ft, and that in unique cases reach 28 ft with axle loads approaching 80,000 lbs. A farmer may be better served by an LWSC if vandals were to set fire to a bridge, or heavy equipment was to cause it to fail structurally.

During periods of dry weather, a primitive road is passable by most vehicles and the LWSC performs suitably. During periods of significant rainfall, the primitive road is only used by farm vehicles, and the closing of the LWSC does not inconvenience the general traveling public.

However, not all obsolete bridges are on a primitive road that serves only as a field access. Other potential locations for an LWSC in which a short loss of access can be tolerated are those that have a suitable alternate route, or detour, but that do not have residences with sole access over the LWSC, a critical school bus route, recreational use, or a critical mail route.

The size of the drainage area can also affect the decision of whether or not to use an LWSC. During high flows on a small watershed, flood waters rise and subside rapidly, whereas on a larger watershed, flood waters rise more slowly and flow over the LWSC for a longer time. It therefore may be tolerable to close a road for a short time as a result of an LWSC on a small watershed. However, it may not be tolerable to close a road for a longer period of time.

Traffic volume as a criterion for LWSC use can be misleading. Significant volumes of traffic indicate a user demand for that particular route. Closing an LWSC with relatively high traffic volumes temporarily increases user costs by diverting traffic to

---

Department of Civil Engineering, Iowa State University, Ames, Iowa 50011.

an alternate route. Another reason that is perhaps more significant is that a larger volume of traffic increases the probability that a user will take chances and cross a flooded LWSC when the road should be closed.

Surfacing or pavement type is not necessarily a criterion for LWSC locations. An unsurfaced road obviously indicates a route of lesser importance. In this case, periodic closing is probably of less concern to the user. However, a high-quality surfacing might indicate a high users' demand for improved facilities on an important route, and therefore a reason for providing a higher level of service.

An LWSC may in fact be applicable when used in combination with an existing obsolete bridge. Consider the situation of a wooden bridge with a substandard width and a lack of structural capability to handle farm equipment. If this bridge was posted so as to preclude all vehicles but automobiles, and a "shoo-fly" vented or unvented ford was provided adjacent to the bridge as shown in Figure 1, both types of users would be served. A situation in which the heavier types of equipment would be unable to use either type of crossing is infrequent.

GENERAL DESIGN CRITERIA

An overview is presented of the entire design process. Because each site is unique and has its own set of conditions, the following criteria and concepts should be viewed as general guidelines that can lead to a well-designed, safe crossing.

Components of an LWSC

An LWSC consists of several components: core materials, foreslope surface, roadway surface, pipes (if it is a vented ford), and cut-off walls or riprap to protect against stream erosion.

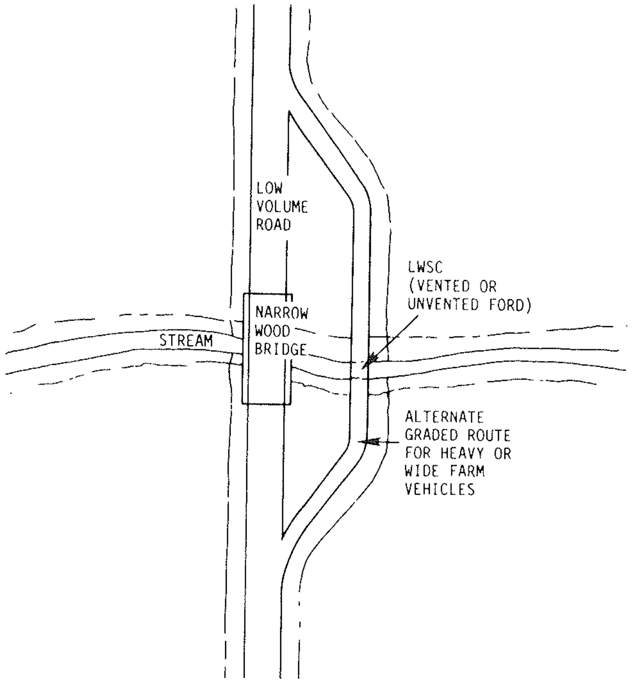

FIGURE 1 Combination obsolete bridge with alternate LWSC for farm equipment.

The core can consist of earth, sand, gravel, riprap, concrete, or a combination of these materials. Erosion protection for the foreslopes can consist of turf, riprap, soil cement, gabions, or concrete. The roadway surface can be composed of similar materials with the provision that a suitable riding surface be developed. The cost and availability of these materials vary from region to region; therefore, the exact composition of the core and surfacing depends on local conditions. Pipes can be shaped like circles, ovals, rectangles, or arches, and can be made of concrete, corrugated metal (CMP), or polyvinylchloride (PVC).

Protection against stream erosion can be provided by either cut-off walls or by armoring the steam bed. Cut-off walls can be constructed of either concrete or steel. The armoring could be in the form of riprap or gabions. The question of whether to use steel, concrete, or rock again depends on the local cost and availability of materials and equipment, such as a pile driver. These components are depicted in Figure 2.

Basic Steps in the Design Process

The general steps involved in the design of an LWSC are diagrammed in Figure 3. The first step is to analyze the location and all the factors that are involved in the decision to build an LWSC. The question of whether to use a ford or a vented ford depends on whether or not water over the road can be tolerated. In most cases an unvented LWSC will create problems as a result of having to close the road for significant periods of time, except in special cases.

The allowable overtopping duration and frequency is a function of local conditions that are unique to each site. Once the percentage of the probability of overtopping (and road closing) has been determined, the overtopping discharge (Q_e) can be calculated. The number and size of the pipe or pipes are then selected so that the head water depth for Q_e just reaches the lowest point in the roadway design.

The crossing grades and elevations are a function of the physical features of the channel and stream banks, and are related to the overtopping discharge headwater depth. The headwater depth and the vertical curve length for a given speed are checked, and the number and size of pipes are then adjusted accordingly.

The selection of material for the crossing foreslopes and the roadway surface is a function of the overtopping velocity and the tractive force, and could range from turf to concrete. The overtopping velocity of the Q overflowing the road is critical until tail water submerging occurs. The final step in the design is to provide protection against stream erosion and seepage.

THE DETERMINATION OF OVERTOPPING FREQUENCY AND DESIGN DISCHARGE

This basic step in the design process requires that a decision be made as to the percent of time in a year the LWSC may be closed; the overtopping discharge (Q_e) can then be calculated.

Overtopping Frequency

The selection of an exceedence probability percent is based on the conditions at the site. The need to have the road open is

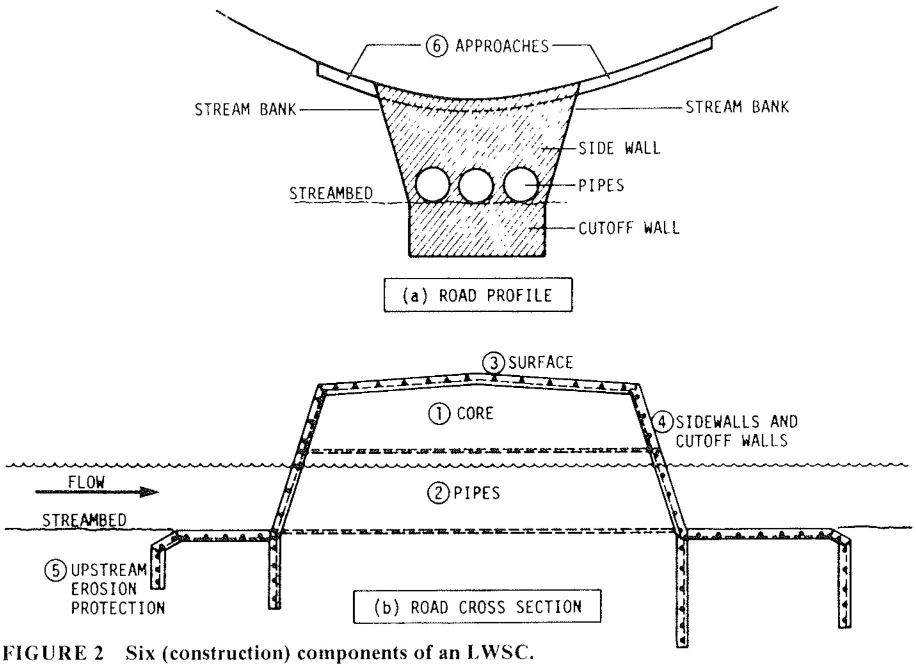

FIGURE 2 Six (construction) components of an LWSC.

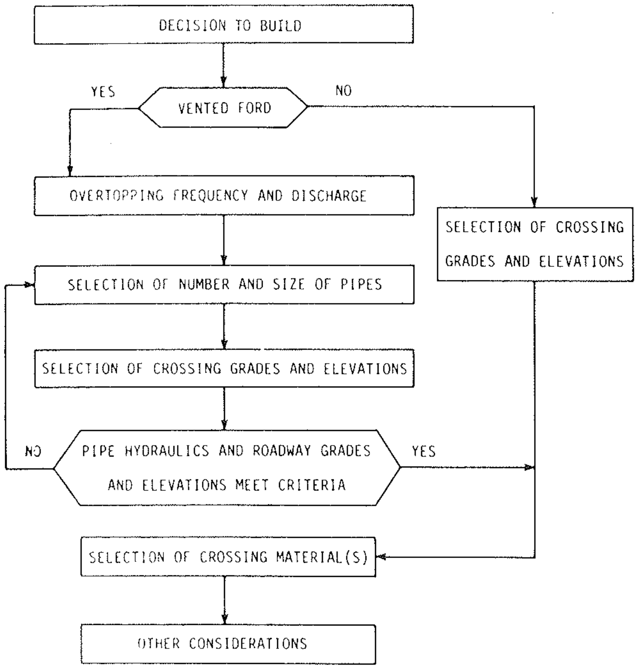

FIGURE 3 General design steps for a low water stream crossing.

based on the type and volume of traffic and the characteristics of the users. A farm field access road with no other traffic could be closed more frequently than a road that serves as access to a home or a school bus route.

A decision to use an exceedence probability of 10 percent would mean that water would flow over the road an average of about 37 days a year. The resulting design discharge would be $Q_{10\%}$. The selection of a design discharge of $Q_{2\%}$ would mean that water would flow over the road an average of one week of the year.

Overtopping Discharge

Once the exceedence probability is selected, the discharge in cubic ft for this probability can be determined by two methods.

If recorded data of daily discharges at the stream location where the LWSC is planned are available, a flow-duration curve can be prepared. This curve indicates the percent of time in which given rates of flow are equaled or exceeded. The curve is prepared by arranging the collected daily discharges in class intervals of ascending order of magnitude. The percent of time during which the flow was equal to or greater than the lower limit of each class is determined and the results are plotted as a flow-duration curve, as shown in Figure 4. The exceedence probability is selected and the discharge is determined from the curve.

Flow-duration information is more frequently needed at stream crossings where no recorded data are available. Low flow records are usually available from the U.S. Geological Survey for certain streams with gaging stations. In some states these data have been statistically analyzed on a regional basis and regression equations have been developed. The form used in Iowa is as follows:

$$Q_e = {}_aA^b$$

where

Q = discharge in ft^3,
e = exceedance probability expressed as a percentage,
A = drainage area in mi^2, and
a and b = regression coefficients peculiar to a particular similar region.

In a case in which no regional equations have been developed, the only technique available is to use adjacent flow-duration curves similar to that shown in Figure 4.

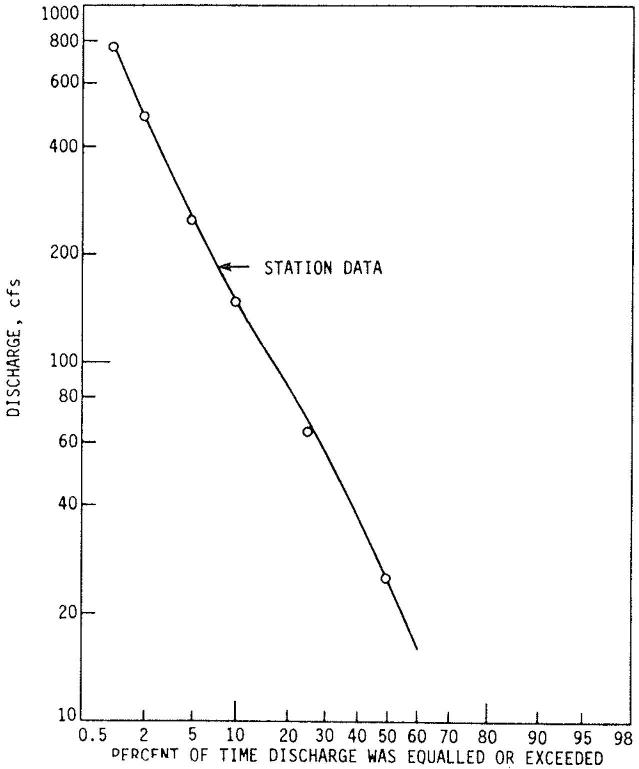

FIGURE 4 Duration curve of daily flow, Timber Creek near Marshalltown, Iowa, 1949-81.

THE DETERMINATION OF THE NUMBER AND SIZE OF PIPES

The determination of the number and size of pipes for a particular site is a trial-and-error process. Several items must be kept in mind: (a) the total width of pipes, including the spaces between them, must be less than the width of the existing channel; (b) the headwater depth controls the low point in the roadway; (c) the pipes may operate under either inlet control or outlet control; (d) pipe lengths are short, but differences in friction losses as a result of pipe material still could be significant; (e) a large difference between the low point in the roadway and the downstream water surface increases the erosion potential on the downstream foreslope; and (f) a large difference between the low point in the roadway and the stream bed increases the volume of material needed in the crossing and, therefore, its cost.

The information needed to determine pipe size is available in Herr and Bossy, "Hydraulic Charts for the Selection of Highway Culverts," *Hydraulic Engineering Circular 5*, GPO, 1964. This publication is commonly known as HEC Number 5 or Bulletin 5. Several combinations of pipe sizes and numbers should be selected for analysis. By using the appropriate chart in Bulletin 5, the headwater depth can then be determined for each combination in a manner similar to a culvert design procedure.

The trial-and-error process begins by determining headwater depths for the estimated overtopping discharge and assumed combinations of pipe material, number, and size operating under inlet control. The results are reviewed in light of the previously mentioned items and the several combinations are reduced to the few best alternatives. These alternatives are checked for outlet control and the final type, size, and number of pipes are selected. If the final low point in the roadway is higher than the calculated headwater depth as a result of roadway criteria, the possibility then exists that the number or size of pipes, or both, could be reduced; this should be checked.

ROADWAY GEOMETRICS

Low water stream crossings are designed for occasional overtopping with floodwater and consequently have an inherent vertical dip characteristic. The approach roadway is at or above the normal ground level on the stream banks, whereas the low point of the crossing may be much closer to the normal water flow surface than a normal culvert design.

This sudden dip in the vertical alignment is inconsistent with drivers' expectations of a public highway profile. Proper signing is essential to alert the driver to a condition that should not be traversed at the higher speeds associated with tangent alignments and flat grades.

The variables of concern in the design of the stream crossing profile are (a) the tangent grades, (b) the length of sag vertical curves, and (c) the length of crest vertical curves at the edges of the stream.

The Determination of Tangent Grades

The determination of tangent grade lines depends on the height of the stream banks, the slope of the terrain adjacent to the stream banks, and the amount of cut allowed into the stream bank. If minimal grading is desired, steep grades will result. A grade of 12 percent should generally provide a surface suitable for driving when wet and muddy, but only at very low speeds. This arbitrary maximum may in fact be increased without undue concern if the vehicles consist of farm equipment and four-wheel-drive automobiles and speeds are very low. Steep grades significantly increase the stopping distance and consequently reduce the allowable speed. However, flat grades that cause a cut-back into the stream bank can result in a maintenance problem. Mud and debris may be deposited by the recession of high water.

The Determination of Vertical Curve Lengths

A number of criteria are recognized in the design of a profile. The criterion of stopping sight distance (d) is usually used to determine the length of crest vertical curves, whereas headlight sight distance, driver comfort, and appearance can be used to determine the length of sag vertical curves.

The normal procedure for designing a crest vertical curve is to provide a sufficient length of vertical curves to enable a driver to bring the vehicle to a stop after discerning an object 6 in high on the roadway ahead. The normal procedure for designing a sag vertical curve is to provide a sufficient length of vertical curve to enable a driver to bring the vehicle to a stop after the headlights illuminate an object on the roadway ahead.

The roadway of an LWSC may be wet and slick. In this case it is appropriate to use a lower friction factor in the stopping sight distance formula. Table 1 has been prepared based on a friction factor (f) equal to 0.20.

TABLE 1 STOPPING SIGHT DISTANCES FOR LOW WATER STREAM CROSSINGS

Velocity (mph)	Perception and Brake Reaction Distance (ft)	Braking Distance (ft)	Stopping Distance (ft)
5	18.4	8.3	27
10	36.8	33.3	70
15	55.1	75.0	130
20	73.5	133.3	210
25	91.8	208.3	300
30	110.3	300.0	410

Figure 5 has been prepared to enable the length of the crest vertical curves at an LWSC to be determined based on an eye height equal to 3.5 ft, an object height of 6 in, and a stopping sight distance from Table 1. Figure 6 has been prepared to enable the length of the sag vertical curves at an LWSC to be determined based on stopping sight distances from Table 1.

THE SELECTION OF MATERIALS

Each crossing has unique characteristics that are peculiar to the region in which it is located and the specific site under

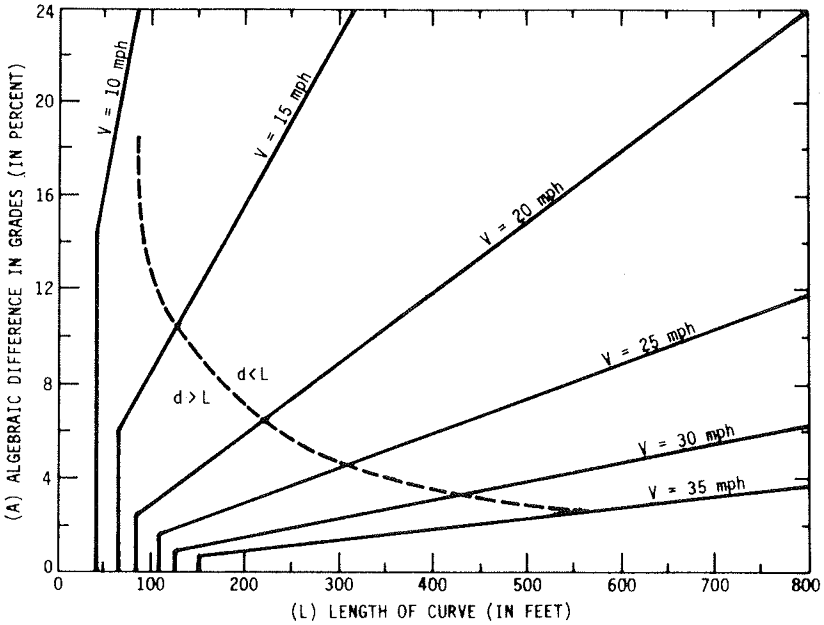

FIGURE 5 Minimum length of crest vertical curve for LWSCs (based on height of eye = 3.5 ft, height of object = 6 in, and stopping sight distance from Table 1).

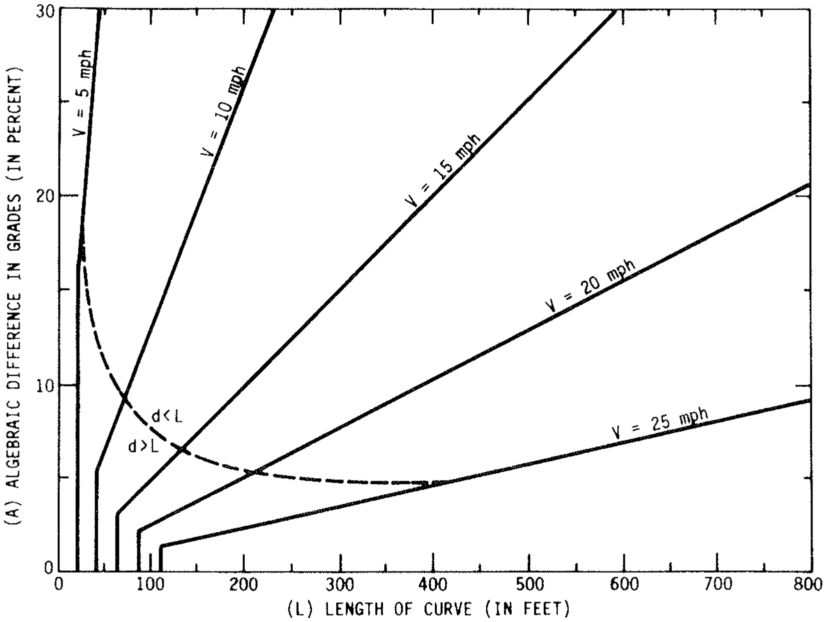

FIGURE 6 Minimum length of sag vertical curve for LWSCs (based on stopping sight distances from Table 1).

consideration. The stream gradient, channel geometry, soil characteristics, costs of materials and labor, and the relative importance of the crossing are all factors of concern.

Various materials can be used ranging from vegetation to Portland cement concrete. Low initial costs may require expensive maintenance. However, a low maintenance design may present overly high initial costs. Each site must be analyzed.

The following items of concern have been selected from studies by the New York Bureau of Soil Mechanics and Keown et al. as considerations in the selection of a suitable material to protect against erosion (*1*, *2*).

- The forces that cause possible failure of the material, whether they be expressed in terms of velocity or tractive force, must be evaluated for each particular material. The specifications of the type or quality of suggested material will depend on the chosen design flood return period.
- The channel geometry in terms of bed slope and bank slope at a particular crossing location will need to be evaluated in order to calculate the forces acting on bank protection.
- Nonuniform settlement as a result of soft foundations and settlement as a result of scouring are important considerations in the design of nonflexible structures such as concrete or Fabriform.
- The environment may have an effect on the material; this includes the action of ice on riprap and sunlight on Fabriform.
- Economic considerations, such as the cost of materials, labor, and maintenance, are an important factor. Alternatives that have a low initial cost might require expensive maintenance, whereas low-maintenance structures might involve an overly high construction cost.
- Aesthetic considerations are considered to be largely unimportant because the structures will generally be located in relatively remote regions; however, this might be an important consideration in state parks.

Vegetative Protection

Two basic types of vegetation can be used as protective materials in crossings: grasses and woody plants. Woody plants take longer to establish than grasses but have the advantage of being more robust and having a greater retarding effect on the stream velocity. This means that woody plants are more suitable for higher velocities. Chow presented data produced by the U.S. Soil Conservation Service on the velocity resistance and retardance characteristics of woody plants (*3*). These data are given in Table 2. The maximum design velocity permitted for the use of grass is 5 ft/sec and is below that which most grasses are capable of resisting. The retardance effect is beneficial because it can reduce velocities close to the bank by up to 90 percent, thereby greatly reducing the eroding power of the flow. However, it has been found that those grasses with the largest degree of retardance also require the best growing conditions.

Environmental conditions for the use of grasses are very important. Steep sideslope angles can create conditions that facilitate erosion. Furthermore, grasses cannot be planted in locations where they will be subjected to anything other than short periodic flows.

A vegetative cover presents an aesthetically pleasing cross-section in a primitive environment at a low cost. Temporary initial protection by the use of a jute may be necessary. Vegetation is also easily maintained or replaced in the case of undermining or settlement.

TABLE 2 PERMISSIBLE VELOCITIES FOR VARIOUS TYPES OF VEGETATION

		Permissible Velocity, fps[1]	
Cover (1)	Slope Range Percent (2)	Erosion-Resistant Soils (3)	Easily Eroded Soils (4)
Bermuda grass	0-5	8	6
	5-10	7	5
	>10	6	4
Buffalo grass, Kentucky bluegrass, smooth brome, blue grama	0-5	7	5
	5-10	6	4
	>10	5	3
Grass mixture	0-5	5	4
	5-10	4	3
	Do not use on slopes steeper than 10%		
Lespedeza sericea, weeping love grass, ischaemum (yellow bluestem), kudzu, alfalfa, crabgrass	0-5	3.5	2.5
	Do not use on slopes steeper than 5% except for side slopes in a combination channel		
Annuals—used on mild slopes or as temporary protection until permanent covers are established, common lespedeza, Sudan grass	0-5	3.5	2.5
	Use on slopes steeper than 5% is not recommended		

[1] The values apply to average, uniform stands of each type of cover. Use of velocities exceeding 5 fps only where good cover and proper maintenance can be obtained.

Rock Riprap

There are three basic types of riprap: dumped, hand-placed, and grouted. The dumped or hand-placed stones constitute a protective lining that is composed of multiple layers of stones that rest on the foundation soil or a bedding layer. The multiple layers ensure that the underlying soil is not exposed if settlement occurs or if scouring by ice or debris occurs.

In terms of cost, the best alternative is dumped riprap, which requires less labor cost. Grouted riprap is the most rigid material and the most susceptible to failure by undermining. Dumped riprap is the material that is least vulnerable to impact damage.

The size and grading of rocks to be used are important. A well-graded riprap acts as its own filter layer and prevents outwash of the underlying soil. A well-graded riprap can be thinner than a uniformly graded riprap with a special filter layer.

Soil Cement

Soil cement can be used as a substitute for riprap. This is especially useful where suitable stone is not available or is costly. Soil cement blocks can be cast at the site and hand-placed to guard against erosion. Soil cement is relatively inexpensive and portions can be replaced with ease. The labor of casting and hand-placing the blocks can be significant.

Soil, sand, and cement have been used to form an erosion-resistant surface. It must be placed under dry conditions and compacted. Shrinkage cracking and a low flexural strength may create problems.

Gabions

Gabions are wire baskets that are filled with stones. They have been used successfully on low water crossings. Reno mattresses and Fabriform are also examples of commercially available slope protection materials.

Gabions have the advantage of being flexible, which makes them less prone to settlement or undermining. They also fill up with silt and can support vegetative growth. Gabions are also usually cheaper than concrete. Suitable rock filler material must be available.

Reinforced Concrete

Reinforced concrete is the most elaborate and costly form of protection; it is also the most durable and requires the least maintenance costs. Designers must consider the use of suitable reinforcement to guard against undermining and scour.

Adjacent Erosion

When selecting a site, the designer should select a location where the stream is stable. If evidence of aggradation, degradation, or lateral migration is evident, an attempt should be made to relocate the crossing or provide remedial measures.

If the designer determines that erosion adjacent to the crossing may occur, erosion-resistant materials or cut-off walls should be provided. The exit velocity, depth of scour, and length of stilling basin must be estimated.

Seepage Considerations

Two potential problems can arise as a result of subsurface seepage beneath hydraulic structures: excessive uplift pressures and piping. The probability of these problems increases with an increasing head difference between the upstream and downstream sides of the crossing. The difference in head may not be large in vented fords, whereas head differences of more than 2 ft might occur in a case in which a ford is used. A flow net analysis was performed using typical ford geometries and sediment properties for a 2-ft head difference. This analysis indicated that, without any cut-off for seepage control, it is unlikely that problems of excessive uplift pressures and high exit gradients will occur; cut-offs for seepage control would therefore be unnecessary. However, if the designer anticipates unusual conditions, a flow net analysis should be conducted to evaluate both pore pressure distribution and exit gradients for conditions of no cut-off and various cut-off geometries.

Although a cut-off may not be justifiable as a means of seepage control, it may be necessary as a protection against scour. The presence of a cut-off wall on the downstream side of a low water crossing will have the effect of decreasing seepage quantities and decreasing exit gradients relative to a condition of no cut-off. However, the cut-off will have a tendency to increase uplift pressures on the downstream side of the crossing. Therefore, it is recommended that if a cut-off is designed for scour control, the structure should be analyzed with a flow net to ensure that the pore pressures are not excessive.

CONSTRUCTION DETAILS

A detailed construction procedure is not practical because of the wide range in the variables of materials and site characteristics. However, certain elements of construction have been successfully used and are included here as examples.

The various components of an LWSC are shown in Figure 2. The design elements were described earlier. The use of cables to hold pipes in place in case the core material is washed out is shown in Figure 7. Examples of side walls and cut-off walls are depicted in Figure 8. These devices are used to protect the edges of the crossing and to prevent erosion of the core filler material. An example of erosion protection for a high type of crossing is shown in Figure 9. The extent to which crossing material can be provided is depicted in Figure 10. Different types of unvented ford protection are shown in Figure 11.

TRAFFIC CONTROL

A low water stream crossing has two unique characteristics that are not associated with a traditional bridge. The vertical profile at the crossing is usually restricted to low speeds and the pavement surface is subject to periodic flooding. Adequate warning of these conditions should be provided to the user. The following recommendations are based on recent research by Carstens and Woo (*4*).

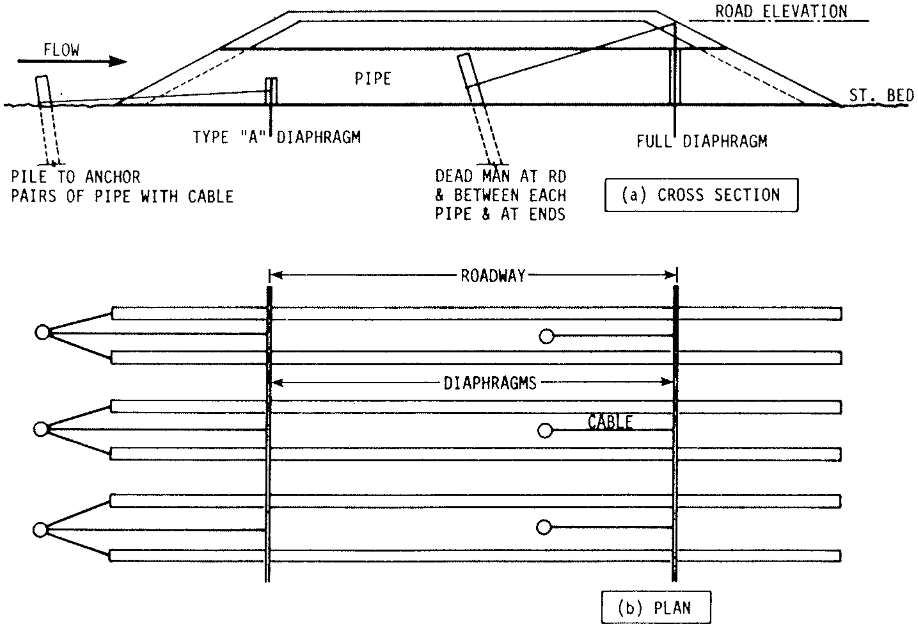

FIGURE 7 Cable anchor details.

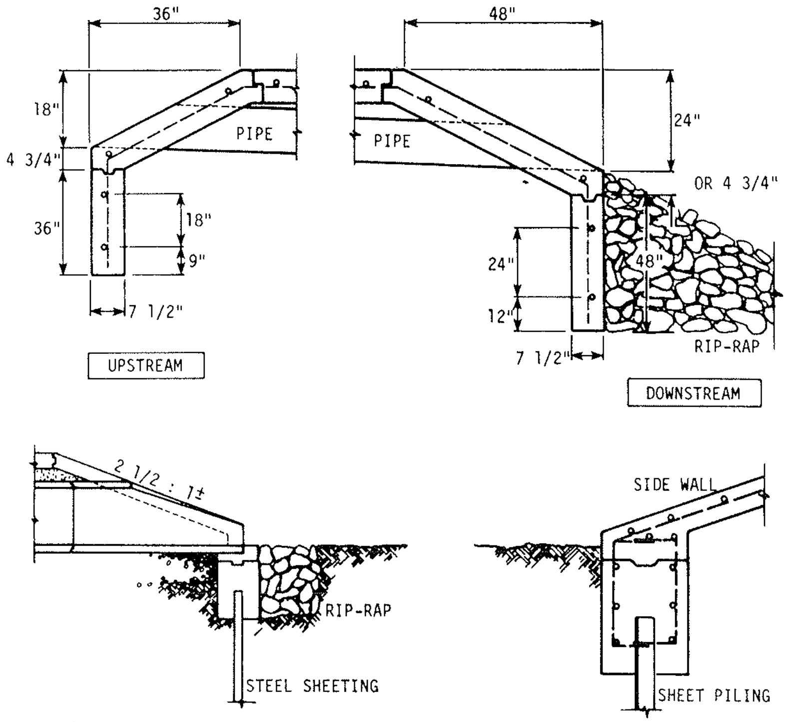

FIGURE 8 Typical sidewall and cut-off wall sections.

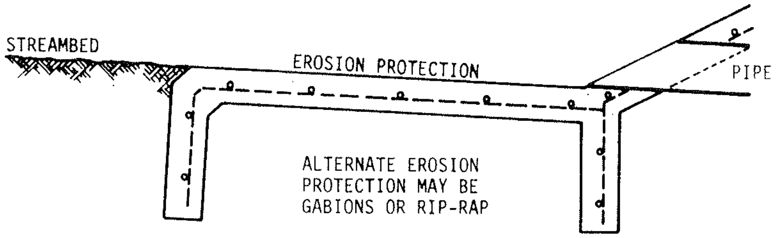

FIGURE 9 Typical erosion protection.

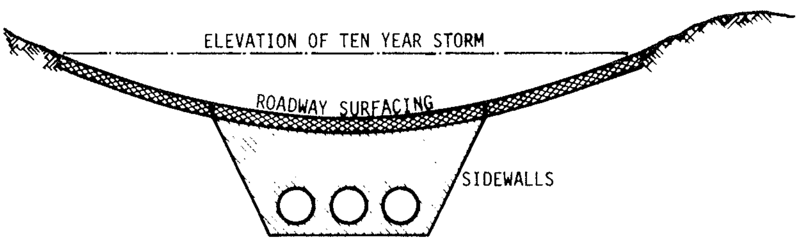

FIGURE 10 Minimum limits of LWSC roadway surfacing.

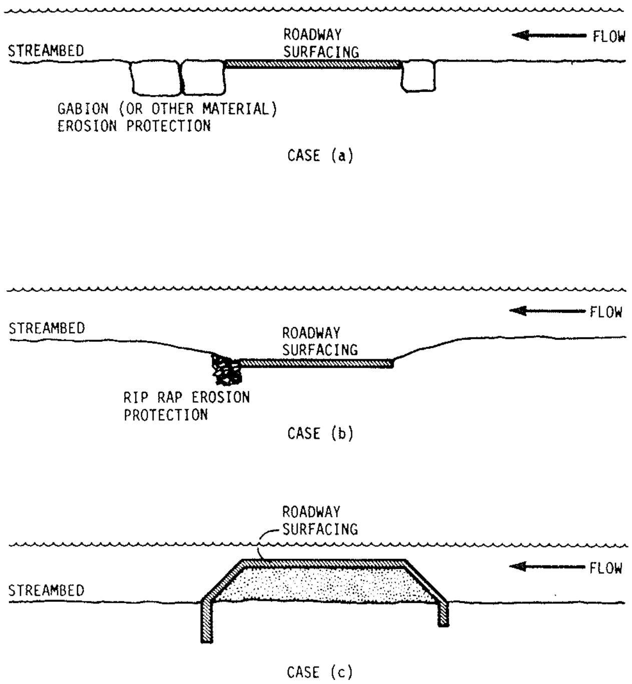

FIGURE 11 Typical fords—roadway cross section.

Application of a Low Water Stream Crossing

In a survey of LWSC use in the United States, 61 percent of the respondents reported they were used only on unpaved roads (*4*). Because paved highways have a geometric design and traffic control that are conducive to higher speeds, drivers' expectations are not consistent with the vertical profile encountered at LWSCs. In addition, because unpaved roads are limited to low traffic volumes, the use of LWSCs on these roads would involve a lower exposure to traffic. Carstens and Woo do not recommend the use of LWSCs on paved roads in Iowa.

The use of an LWSC design is based on an acceptance of periodic flooding. If flooding would isolate a place of human habitation, either an alternate design should be considered or an alternate emergency access route should be developed.

Approach Signing

The signing recommendations shown in Figure 12 are based on Carstens' and Woo's research (*4*). The recommendations were subsequently adopted by the Iowa DOT as recommended practice. According to Carstens and Woo, the intent of the regulatory sign DO NOT ENTER WHEN FLOODED is to preclude travel across the LWSC when the roadway is covered with water (*4*). Such a regulatory sign requires a resolution by the Board of Supervisors. The adoption of this sign in effect significantly reduces the applicability of an unvented ford.

Supplemental Signing

If the location of an LWSC is not apparent from a point approximately 1,000 ft in advance of the crossing, a supplementary distance plate may be used. The message "700 feet" would be displayed with the FLOOD AREA AHEAD sign. The sign would be 24 in × 18 in with a black legend on a yellow background.

An advisory speed plate may be used if the maximum recommended speed at the LWSC is less than the speed limit in effect, which is usually the case. The advisory speed plate would be installed in conjunction with the FLOOD AREA AHEAD sign. However, if a supplemental distance plate is used, the advisory speed plate would be installed in conjunction with the IMPASSABLE DURING HIGH WATER sign.

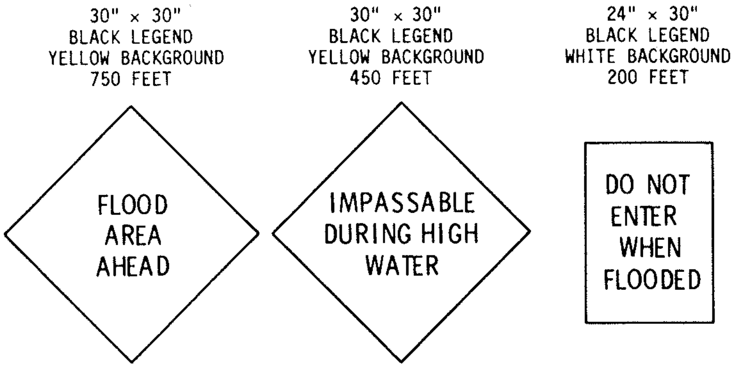

FIGURE 12 Signs recommended for installation at low water stream crossings.

Controls at a Low Water Stream Crossing

Various controls have been used to delineate the edges of the traveled way at an LWSC. Curbs are generally unacceptable because the flow of water tends to deposit mud and debris on the roadway. Attempts have been made at a few locations to create a series of small, raised curb blocks with tapered upstream slopes to provide for a smooth laminar flow. The use of any projections above the normal roadway surface will have an adverse effect on the self-cleaning aspect of the smooth cross-section. However, observations of existing applications, or further research in this area, are needed.

REFERENCES

1. *Soils Design Procedure SDP-2: Bank and Channel Protective Lining Design Procedures.* Bureau of Soil Mechanics, State of New York Department of Transportation, Albany, 1971.
2. M. P. Keown, N. R. Oswalt, and E. B. Perry. *Literature Survey and Preliminary Evaluation of Streambank Protection.* WES Report RE-H-77-9. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Miss., 1977.
3. V. T. Chow. *Open-Channel Hydraulics.* McGraw-Hill Book Company, New York, 1959.
4. R. L. Carstens and R. Y. Woo. Liability and Traffic Control for Low Water Stream Crossings. *Engineering Research Institute Project 1470 Final Report.* Iowa State University, Ames, 1981.

Guidelines for the Design of Low-Cost Water Crossings

LOUIS BERGER, JACOB GREENSTEIN, AND JULIO ARRIETA

In Ecuador, as in many Third World countries, low-volume rural roads can only be economically justified when very low-cost bridges and simple water crossings (fords) are used. Traffic analyses indicate that in most cases the trucks that travel these roads carry loads that weigh less than 6 to 10 metric tons. Therefore, most of the drainage structures are designed to carry only 10 tons on two-axle light vehicles. Roads are designed according to AASHTO HS-15 standard loading in those locations where heavy traffic is generated from timber production or banana plantations. The standard AASHTO HS-20 live load cannot be economically justified for these low-volume roads. The traffic volume in rural regions is very low, which enables such economical structures as graveled fords to be used, and, when economically feasible, one-lane bridges with either complete or split decks. The relationships between the type of material, the span or length of the superstructure, and the cost are analyzed. It is primarily concluded that simple timber bridges made of stringers and transverse laminated decks are the most economical solutions for simple spans up to 17, 14, and 10 m for 6-, 10-, and 24.5-ton truckloads, respectively. Simple-span, split-deck, reinforced-concrete superstructures are feasible for spans of up to 30 m. Spans can be as long as 45 m if prestressed girders are used. Suspension bridges with timber decks and timber-stiffening trusses were built to carry 6-ton trucks or cattle wagons and were more cost-effective than timber or concrete structures. It was concluded that with the judicious reduction of the design standards of live loads, cross-sections, geometry, material specifications, and hydrologic and hydraulic considerations, construction costs could be reduced by 50 percent or more. These savings make it possible to justify the construction of many low-volume rural roads that would otherwise be impossible to finance.

Low-volume roads are needed in such developing countries as Ecuador and Colombia to provide access in agricultural and rural regions (*1, 2*). A socioeconomic analysis is performed to determine which type of road is the most economical to build. The use of this methodology enables the least-cost road to be determined for any given traffic projection, degree of agricultural productivity, and extent and type of social and population activities.

Several types of low-cost rural roads exist in Ecuador: (a) earth or dirt roads that are 2.5 to 4.0 m wide and provide access only during the dry season, (b) 4.0- to 6.0-m-wide compacted subgrade or gravel roads, (c) 4.0- to 5.0-m-wide stone roads constructed mainly in the Andes region, and (d) 6.0- to 7.2-m-wide base course roads with or without blacktop. Construction of most of these low-volume roads can be economically justified only if the construction cost is minimized to achieve a feasible rate of return on the investment. The minimum initial rate of return required to justify investment in the construction of low-volume roads in Ecuador in 1984 to 1985 was 12 percent. This objective can be achieved only if low-cost water crossings are used to provide access.

Louis Berger International, Inc., 100 Halsted St., East Orange, N.J. 07019.