Gabions Used in Stream Grade-Stabilization Structures: A Case History

G. J. HANSON, R. A. LOHNES, and F. W. KLAIBER

ABSTRACT

Streams in western Iowa have been degrading since the turn of the century and this entrenchment has endangered many highway and railroad bridges. Although grade-stabilization structures have been effective in controlling this erosion, the cost of reinforced-concrete structures has risen to the point that less expensive materials need to be considered. In an effort to evaluate alternative materials for this purpose, a gabion drop structure was designed and built and its performance monitored for 2 years after completion. The demonstration structure has performed satisfactorily with minimal differential settling and minor erosional problems downstream of the structure. Sedimentation occurred upstream of the structure during construction but little additional sediment has accumulated since. A cost analysis that normalizes several variables is used to compare the gabion structure with concrete structures and indicates that the cost of building the gabion structure was about 20 percent of that of a comparable-size concrete structure. It is concluded that this type of structure is an effective and economic alternative.

Since the turn of the century, tributaries to the Missouri River in western Iowa have entrenched their channels to as much as six times their original depth. This channel degradation is accompanied by widening as the channel side slopes become unstable and landslides occur. The deepening and widening of these streams have endangered about 25 percent of the highway bridges in 13 counties (1).

Grade-stabilization structures have been recommended as the most effective remedial measure for stream degradation (2). In western Iowa within the last 7 years, reinforced-concrete grade-stabilization structures have cost between $300,000 and $1,200,000. Recognizing that the high cost of these structures may be prohibitive in many situations, the Iowa Department of Transportation (Iowa DOT) sponsored a study at Iowa State University (ISU) to find low-cost alternative structures. Analytical and laboratory work led to the conclusion that alternative construction materials such as gabions and soil-cement might result in more economical structures (1). The ISU study also recommended that experimental structures be built and their performance evaluated.

The supervisors of Shelby and Pottawattamie counties agreed to participate in the construction of these demonstration structures; the counties were to provide 25 percent of the construction costs and the Iowa DOT Highway Research Board was to provide 50 percent. The Iowa State Water Resources Research Institute (ISWRRI) provided sufficient funds for 25 percent of two structures, one in Shelby County and the other in Pottawattamie County.

CONSTRUCTION COSTS AND PROBLEMS

Plans were developed for a soil-cement structure in Shelby County and a gabion structure in Pottawattamie County. The original cost estimate for the Shelby County structure was about $60,000; however, the final cost estimate was twice that because of problems anticipated with the excavation of the stilling basin. No bids were received at the scheduled March 1982 letting, and the construction money allocated to this project reverted to ISWRRI and was reallocated to other projects within the Institute.

Although the laboratory studies at ISU suggested that soil-cement was a feasible construction material for grade-stabilization structures (3), the lack of any contractor willing to bid on the project indicated that a major practical problem existed with the use of soil-cement in this type of structure. The problem may have been associated with conditions at this specific site or with the lack of contractor experience in constructing soil-cement water-control structures. A third possibility was that the contractors did not accept the results of the laboratory studies and needed evidence of the field performance of such structures. If lack of construction experience was the reason for the lack of bids, specifications outlining construction procedures need to be developed. If the third reason was the primary cause for the lack of bids on the Shelby County structure, field scale research needs to be conducted to support or reject the validity of the laboratory work. It is the Shelby County engineer's opinion that lack of contractor experience in mixing and placing soil-cement was the major problem; in addition, the practical construction problems may drive the cost of the structure so high that they will offset any savings in material cost (Eldo Schornhorst, personal communication, Nov. 7, 1984).

The Pottawattamie County gabion structure was originally estimated at a cost of $60,000, but after detailed design and modifications suggested by the county engineer, the cost estimate increased to $85,000. Bid letting was September 16, 1982, when three bids were received; the lowest was $97,000. The required additional funds were provided by the county supervisors, and construction began November 29.

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

Except for 4 weeks during January, construction continued through the winter. Although several problems were encountered during construction, the contractor was able to get water through the structure by May 16. The structure was completed by June 30, 1983, at a final cost of $108,000. The cost overrun was due largely to construction problems. A comparative cost analysis of this gabion structure and reinforced-concrete structures is presented later in this paper.

DESCRIPTION OF GABION GRADE-STABILIZATION STRUCTURE

The demonstration gabion grade-stabilization structure is located on Keg Creek 3 mi east of McClelland at Section 1-75-42. The drop structure is situated 100 ft downstream from a bridge where, since 1958, 14 ft of channel degradation has exposed bridge piers and caused landslides that removed soil from the east abutment. The drainage area of Keg Creek at this location is approximately 90 mi^2. Before construction, the stream gradient was from 6 to 8 ft/mi with a channel width of about 50 ft at the top.

The structure consists of a gabion wier and ramp with a net drop of 12.6 ft, which is intended to reduce the effects of the degradation at the bridge site. Figure 1a and b show the plan and profile of the structure. The bottom width of the weir and ramp is 21 ft with 2:1 side slopes extending 27 ft upward. Figure 1c is the plan of the gabion arrangement. Gabions 1 ft by 3 ft and 3 ft by 3 ft were used. The ramp is 51 ft long with a 4:1 downstream slope. The stilling basin is 63 ft long. The fill rock in the gabions has a maximum rock size of 8 in. with 75 percent greater than 4 in. and not more than 5 percent passing the 1/2-in. sieve.

The structure was designed for the 50-year-frequency flood of 9,930 ft^3/sec to contain the hydraulic jump and avoid overbank flooding. As a point of comparison, the 2-year-frequency flood is estimated at 2,190 ft^3/sec. Before construction of the structure, the channel had the capacity to contain the 100-year-frequency flood of about 12,000 ft^3/sec. It is expected that the structure will cause a 4-ft rise in the water surface elevation upstream of the structure during the 100-year flood but will not cause overbank flow.

Monitoring Performance

The monitoring of the structure included differential settlement measurements, measurements of upstream aggradation and downstream degradation subsequent to placement of the structure, measurements of stream flow through the structure, and qualitative observations of structural deterioration.

Settlement Measurements

In order to monitor the differential movement of the structure, concrete monuments were placed on the

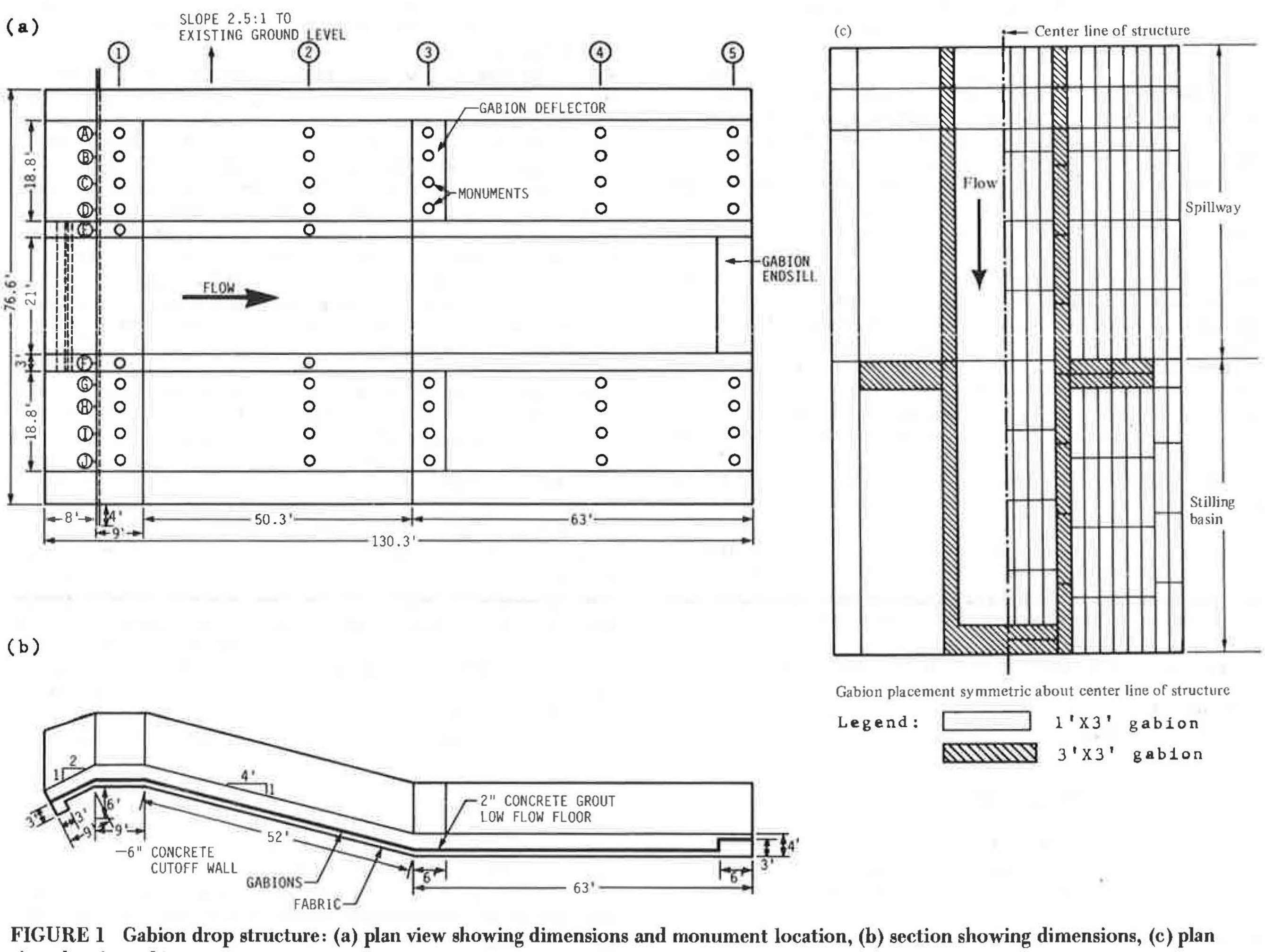

FIGURE 1 Gabion drop structure: (a) plan view showing dimensions and monument location, (b) section showing dimensions, (c) plan view showing gabion arrangement.

surface as shown in Figure 1a. Elevations of the monuments were measured at five different times: June 29 and November 17, 1983; June 8 and August 22, 1984; and June 5, 1985. The elevation data were used to plot all five of the transverse cross sections at the various dates. These plots revealed that virtually no differential settlement occurred within the structure throughout the course of the investigation. Figure 2 is a typical cross section, and Figure 3 is the cross section at about the middle of the structure. In Figure 3, Monument 1A (at the top of the side slope immediately downstream from the crest) settled about 4 in. between the first two observation dates. No differential movement has been observed since November 17, 1983; thus it has been concluded that differential settlement is not a problem. Because soil consolidation occurs most rapidly soon after loading, it appears that settlement will not be a problem.

Observations of Deterioration

Minor deterioration of the structure is being observed visually and has been recorded in photographs. Some deformation of the side slope is apparent in the vicinity of Monuments 2D and 2E, but this movement occurred during construction after a high-runoff event. Because runoff had filled the channel, the contractor, in an effort to dewater the site and resume work quickly, pumped the water out of the channel in a short time. It is interpreted that this rapid drawdown condition created instability and caused slippage. A rapid drawdown condition is not likely to occur during normal operation of the structure; consequently, the side slopes are expected to be stable in the future. The stability of the side slopes is verified by the constant elevations of the monuments. Although the observed slope deformation is not of great concern, anchors were placed on the slope as a precaution.

A scour hole has developed immediately downstream of the stilling basin on the west bank. The hole is roughly 10 ft long parallel to the channel and extends about 3 ft into the bank. This is where the construction diversion channel was located, and the backfill in this area may have been improperly compacted. The scour hole should be continuously observed for any signs of expansion. If erosion proceeds in the upstream direction, it may undermine

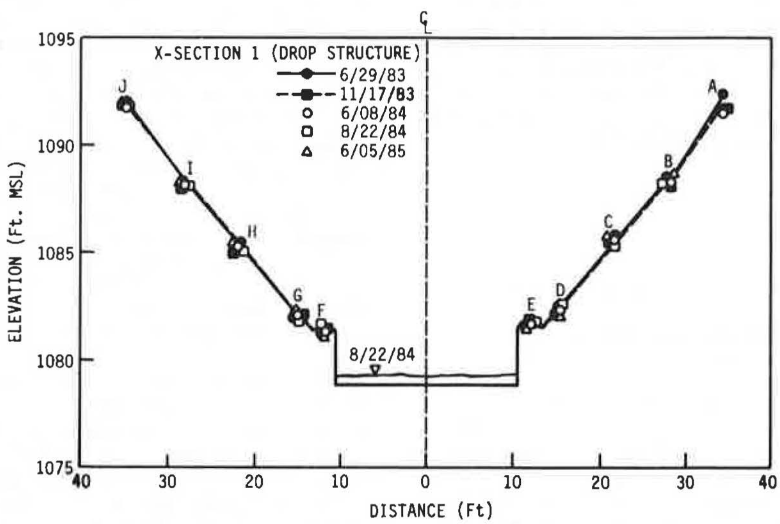

FIGURE 2 Cross section at top of structure (note differential movement at monument 1A, the only measurable movement observed in the structure).

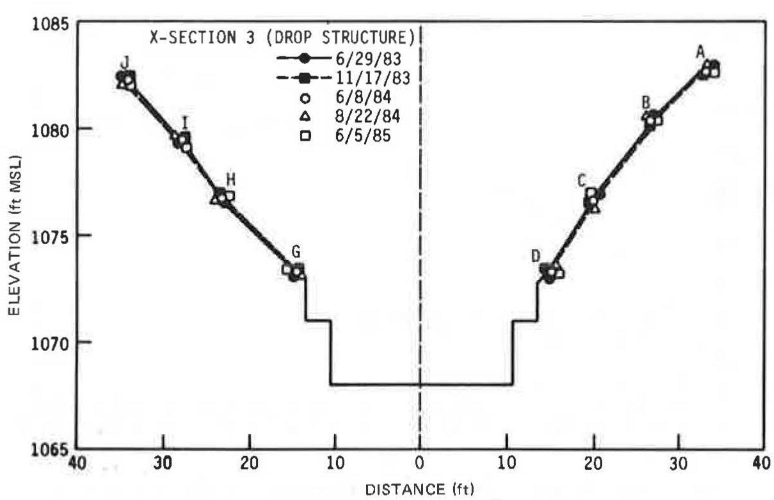

FIGURE 3 Cross section at about middle of structure.

the side slope and stilling basin. If the hole expands, it should be protected with riprap or additional gabions.

Flow Estimates

Seven gauges to measure stream flow were placed on the bridge piers and on posts upstream and downstream of the bridge within a 3-mi reach. Each gauge consists of a vertical tygon tube attached to a staff gauge. The tube has a one-way valve at the bottom that allows water to flow into but not out of the tube. The gauges were positioned on the posts to measure high-flow events only. Water enters the bottom of the tygon tubing through the one-way valve and rises in the tube as the stream stage rises. After the maximum stage has been reached, the water is trapped in the tube by the one-way valve. This allows measurement of the maximum stage from the staff gauge attached to the tube. The gauges have not functioned as well as anticipated. Debris has plugged the one-way valves and prevented the collection of data. For future applications of these gauges, an attempt should be made to design some type of debris trap on the intake end of the system.

Because the gauges failed to perform adequately, an alternative method of estimating flows was devised. The spillway structure produces critical flow at its crest and therefore acts as a control in the stream channel. Controls are defined as certain features in a channel that tend to produce critical flow (4). At any feature that acts as a control, if the flow depth is known, the discharge can be calculated by using the following relationship:

$$Q = A(gA/B)^{1/2}$$

where

- Q = discharge flowing through the crest of the spillway (ft^3/sec),
- A = area of the wetted section (ft^2),
- B = corresponding width of the water surface (ft), and
- g = acceleration due to gravity (32.2 ft/sec^2).

The geometry of the spillway crest of the gabion grade-control structure was used to calculate the discharge for various depths of flow from the foregoing equation; that relationship is shown in Figure 4. Details of the calculation may be found in a report by Hanson et al. (5). Note that for the 50-year flood frequency with a discharge of 9,930 ft^3/sec, the depth of flow through the structure is 14 ft. For the design of this structure the HEC-2 backwater calculation program was used, and it estimated the flow depth at 13.5 ft. The data shown in Figure 4 are in good agreement with the design estimates.

Debris deposited on the sidewalls of the structure during a flood event are physical evidence of the maximum stage for that event. The elevations of the debris lines were measured during summer 1983 and spring 1984 and on June 8, 1984, and June 5, 1985. These depths of flow are plotted in Figure 4 and indicate that, to date, the flows have been well below the design flood with discharges less than 1,200 ft^3/sec.

The water-surface profile for the design flow of 9,900 ft^3/sec was estimated with the HEC-2 program. The design water-surface profile and the water-surface profiles for 120- and 1,200-ft^3/sec discharges, which were estimated from the debris lines, are shown in Figure 5. These curves suggest that the downstream effects of the structure and stream force the hydraulic jump upstream onto the spillway to create a submerged jump.

Sedimentation Observations

Changes in the upstream channel geometry caused by sedimentation have been monitored by surveying transverse profiles at the bridge and at 500-ft intervals upstream to a distance of 5,000 ft. Transverse profiles at the bridge were measured on June 28 and November 17, 1983; June 8 and August 22, 1984; and June 5, 1985. Before construction the slope of the stream was 13.2 ft/mi. A set of transverse profiles is shown in Figure 6. These sections show that sedimentation to a depth of 6 ft had occurred before June 28, 1983, but little change has been noted since then. This indicates that the major amount of sedimentation above the crest occurred during construction and that the 1,200-ft^3/sec event since construction has had little effect on deposition.

A longitudinal profile surveyed on August 23, 1984, is shown in Figure 7. The water surface extends 5,500 ft upstream from the crest of the structure and the sediment surface extends approximately 4,000 ft upstream from the structure. It is expected that this sediment will extend further upstream in the future. A conservative estimate is that it will continue to the point where the water-surface profile intersects the streambed profile, that is,

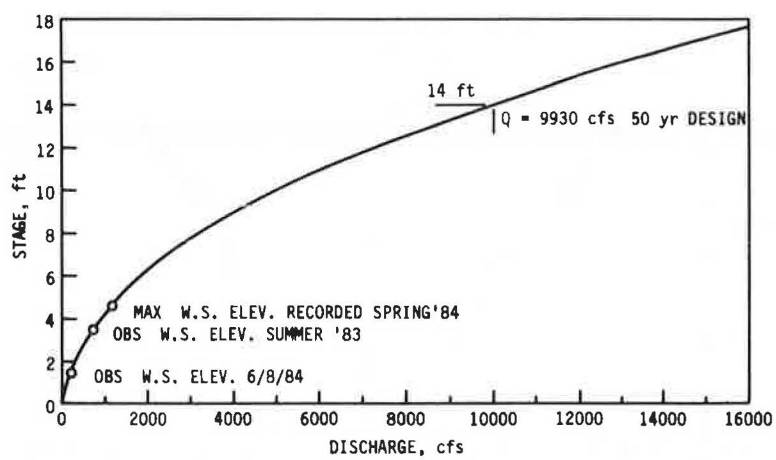

FIGURE 4 Stage-discharge relationship for drop structure at its crest (elevation, 1,079 ft above mean sea level).

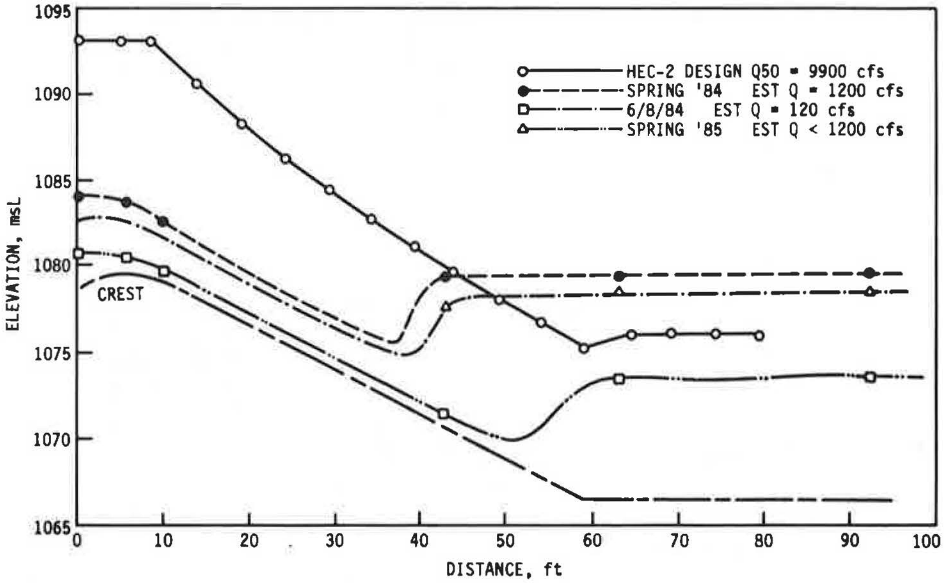

FIGURE 5 Water-surface profiles from HEC-2 for design and as estimated from debris lines at various dates.

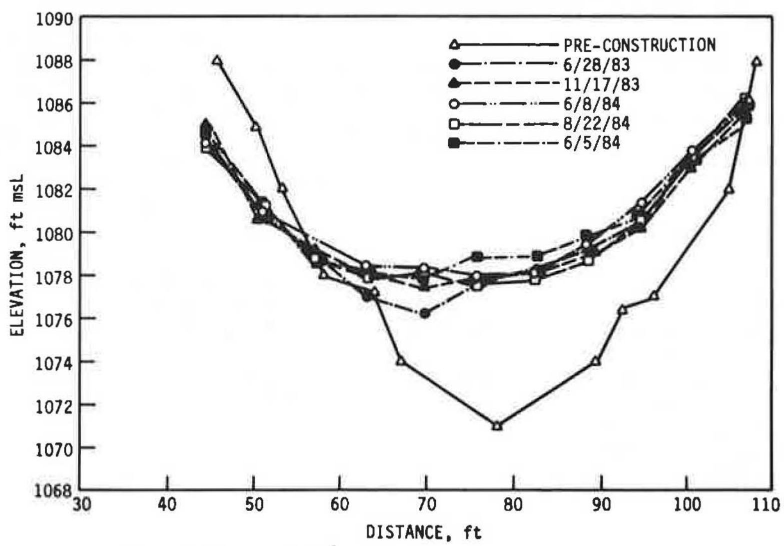

FIGURE 6 Transverse cross sections of channel bottom for various dates.

about 5,500 ft. This would produce a slope of about 5.7 ft/mi.

A less conservative estimate of the ultimate upstream extent of the sediment is calculated from the method suggested by Maccaferri (6). The stable slope of a channel can be estimated from the following equation:

$$i = (vu)_{\ell}^{10/3} B^{4/3} n^2 / Q^{4/3}$$

where

- i = stable slope,
- u_{ℓ} = maximum permissible velocity (which depends on the size of bed material at which bed erosion starts),
- v = ratio between mean water velocity and the corresponding velocity at the channel bottom,
- B = wetted perimeter,
- n = roughness coefficient, and
- Q = design flow.

This relationship is an extension of Manning's equation, and the detailed analysis with application to the gabion structure has been given by Hanson et al. (5). That analysis estimated a stable slope of 4 ft/mi, which would cause the sediment to extend upstream for about 6,500 ft. That slope is also plotted in Figure 7, where it can be seen that the wedge of sediment would intersect the knickpoint at about midheight. Depending on the estimate used, the grade-control structure has reduced the slope of the stream to 30 or 40 percent of the original and thereby caused aggradation.

Even though the sedimentation effects of the structure may extend 6,500 ft upstream, there is field evidence that the channel banks are barely stable and that sloughing of the side slopes may cause further loss of land and damage to roads. Also, the upstream knickpoint was not submerged by the grade-control structure, so it is likely that the knickpoint will continue to progress upstream.

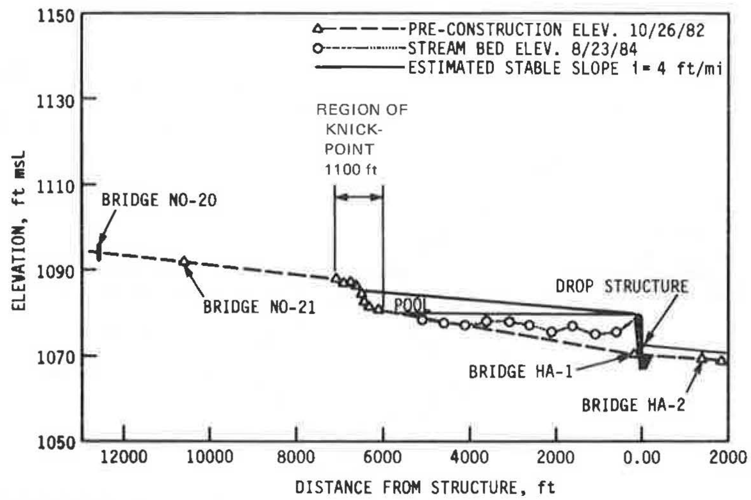

FIGURE 7 Longitudinal profile of channel bottom and water surface in pool upstream of structure.

Downstream Erosion

Bank erosion is occurring downstream beyond the stilling basin to a distance of approximately 80 ft. This may be partly because of the submerged jump, which was discussed earlier. The submerged jump provides relatively inefficient energy dissipation, which may be cause for future concern. An extension of the stilling basin may be required to provide better energy dissipation.

ECONOMIC COMPARISON OF GABION STRUCTURE WITH CONCRETE STRUCTURE

The major objective of this research was to find low-cost alternatives for the stabilization of degrading streams. In western Iowa, the conventional approach to grade stabilization has been the use of reinforced-concrete drop structures. In Pottawattamie County gabions have served well in various applications for over 10 years, and it is thought that the service life of a gabion structure is essentially equivalent to that of a reinforced-concrete structure.

It is difficult to compare the cost of the gabion drop structure that was built and evaluated as part of this study with the cost of reinforced-concrete structures that have been used in the past because the cost of the structure increases with increasing size, slope, drainage area, and design discharge. The cost of four reinforced-concrete drop structures that were constructed in western Iowa within the last 7 years and that of the gabion structure are shown in Table 1. These data are the 1982 costs based on Iowa DOT's construction index; the calculations of these costs may be found elsewhere (5). Although the gabion structure is less than one-third the cost of the least expensive concrete structure, it also has the smallest drop. On the other hand, the gabion structure has the second-largest drainage area and the largest design flow of the structures listed. The foregoing comparisons illustrate the problem. In order to develop a normalized size and discharge factor that would account for all the size and hydrologic variables, a dimensional analysis was performed to incorporate all the relevant properties into one term that could be used for the cost comparison of the structures.

Design discharge and structure width can be combined to provide a flow area at the crest based on the assumption that critical flow occurs at the crest of the structure (4):

$$A = (Q^2B/g)^3$$

where

- A = area of the wetted section at the critical depth,
- Q = design flow,
- B = corresponding width of the water surface, and
- g = acceleration due to gravity.

The wetted section (A) has been calculated for the five drop structures and the data are shown in Table 2.

The wetted area can be combined with drainage area (D.A.) to form a semidimensionless term:

$$a = D.A./A$$

TABLE 1 Geometry, Design Discharge, and Cost of Grade-Control Structures in Western Iowa

Structure Type and County	Creek	Drainage Area (mi^2)	Slope (ft/mi)	Drop (ft)	Length (ft)	Width (ft)	Design Q (ft^3/sec)	Cost[a] ($)
Reinforced-concrete structures								
Harrison	Willow	67.2	9.3	38.4	142	67.5	5,800	376,022
Monona	Willow	32	19.5	36.6	142	67.5	7,500	372,447
Harrison	Willow	100.2	8.3	24.0	115	80.0	7,250	434,562
Harrison	Pigeon	56.5	8.0	18.6	110	80.0	8,100	345,147
Gabion structure								
Pottawattamie	Keg	90	8.0	12.6	131	—[b]	9,930	101,000

[a] 1982 costs based on Iowa DOT construction index.
[b] Stilling basin is trapezoidal with average width of 51 ft.

TABLE 2 Dimensional Analysis to Develop Size Factor for Cost Comparison of Structures

Structure Type and County	Creek	A (ft)	a (mi^2/ft^2)	Sc (ft/mi)	Sc (ft/ft)	aScSs (mi/ft)
Reinforced-concrete structures						
Harrison	Willow	413.1	0.163	9.38	3.70	5.63
Monona	Williow	490.7	0.065	19.5	3.88	4.92
Harrison	Willow	507.3	0.198	8.33	4.79	7.90
Harrison	Pigeon	546.3	0.103	8.00	5.89	4.85
Gabion structure						
Pottawattamie	Keg	602.0	0.100	8.00	10.35	12.43

The term is semidimensionless because the drainage area is in square miles and the wetted area is in square feet. The values of a for all five structures are also shown in Table 2. The channel slope (Sc) is a semidimensionless term in feet per mile, and a dimensionless term (Ss) can be generated by dividing the overall length of the structure by its drop. These terms, along with their combined values, are shown in Table 2. This combined term describes the structure according to size, design flow, and drainage area and is defined here as the size factor. The cost of each structure is plotted versus the size factor in Figure 8; it can be seen that the cost of the concrete structures increases linearly with increasing size factor. Note that the cost of the plotted gabion structure versus its size factor falls considerably below the line projected for the concrete structures. This analysis suggests that the cost of the gabion structure may be about 20 percent of the cost of an equivalent reinforced-concrete structure.

CONCLUSIONS

The gabion grade-stabilization structure has shown satisfactory structural performance throughout the 2-year observation period, with minimal differential settling and no evidence of side-slope instability since construction was finished. It should be recognized that the maximum flow to date has been less than 15 percent of the design flow.

The major amount of sedimentation occurred during construction and is likely to extend at least 5,500 ft upstream of the structure. A more optimistic estimate is that the depositional wedge will extend 6,500 ft upstream. In any event the sedimentation effects of the structure will not submerge the knickpoint that exists upstream, so continued erosion problems are likely upstream of the sedimentation area.

The sedimentation beneath the bridge has been sufficient to cover the piles to their original depth of soil cover and to stabilize the slope beneath the abutment.

Erosion downstream of the structure could be a problem, especially if it undermines the stilling basin. However, the gabions are deformable and may collapse into any scour hole that forms, thereby becoming somewhat self-protecting. This downstream erosion is the result of inefficient energy dissipation by the stilling basin.

An analysis of the cost of the gabion structure as compared with costs of four concrete structures included the size, drainage area, and design flow of each of the structures. This analysis suggests that the cost of the gabion structure is about 20 percent of that of an equivalent concrete structure.

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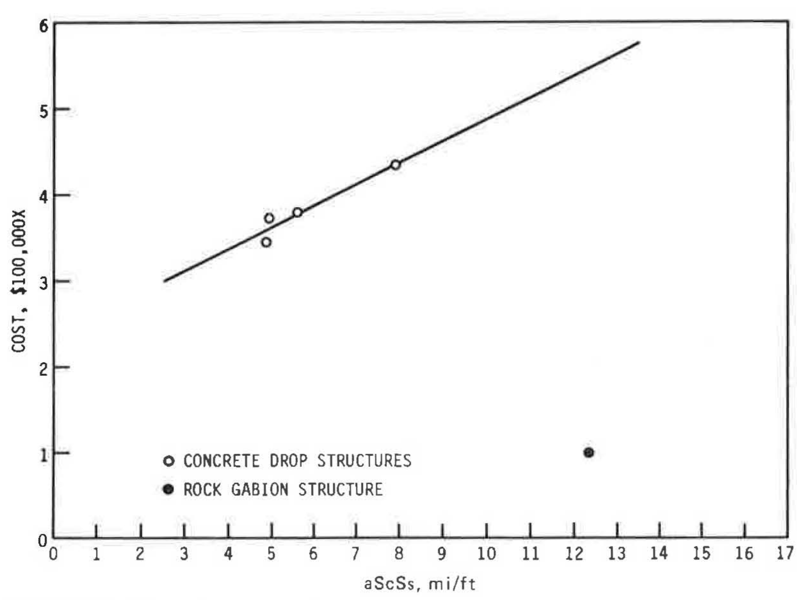

FIGURE 8 Dimensionless size factor versus construction costs for four concrete drop structures and one gabion drop structure.

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