MUDDY CREEK GRADE CONTROL STRUCTURES, MUDDY CREEK, MISSISSIPPI AND TENNESSEE

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INTRODUCTION

Muddy Creek is located in extreme north Mississippi and south Tennessee and flows generally north from Ripley, Miss., to the Hatchie River just north of the Mississippi-Tennessee State line. Between September 1976 and September 1983, the Soil Conservation Service (SCS) modified the Muddy Creek system by constructing a trapezoidal channel with 12 riprap grade control structures spaced along the main channel. The first four structures (structure No. 1 being the farthest downstream) and connecting channel were constructed between September 1976 and February 1980, using the procedures in SCS's TR-59, "Hydraulic Design of Riprap Gradient Control Structures" (reference 1). Surveys of the structures during 1980 indicated that severe scour, up to 15 ft. deep, had occurred immediately downstream of several structures. Postulated as a cause for the scour was flow separation in the 1 on 4 exit flare which caused eddies to form along the side slopes resulting in flow concentrations in the channel. The remaining grade control structures were constructed with a 1 on 8 exit flare in an effort to improve exit flow conditions. Heavier riprap was placed at the downstream end of the prismatic section and the upstream portion of the exit flare. However, scour holes again formed immediately downstream of these structures.

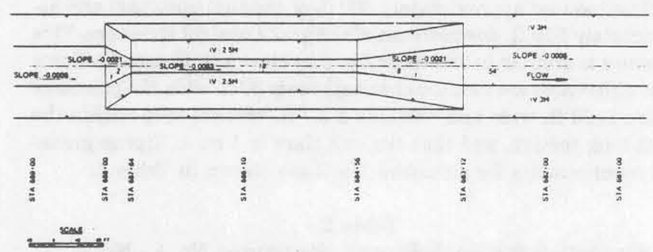
A model investigation was conducted to determine the flow conditions that were causing the observed scour and to develop modifications to the existing structures to minimize the scour conditions. Additionally, the model study was used to develop design modifications to prevent the flow conditions causing scour.

THE MODEL

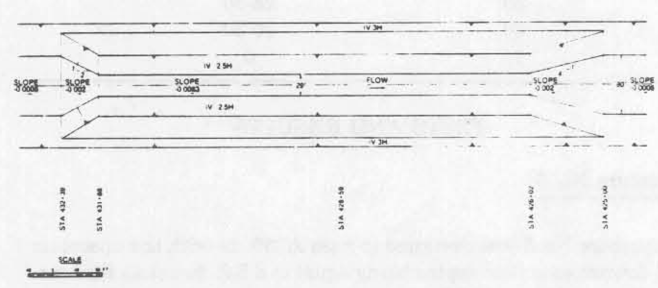
Field observation of the completed Muddy Creek system, consisting of grade control structures No. 1 through No. 12, indicated that the maximum amount of scour had occurred at structure No. 5, where the channel bottom had scoured significantly with subsequent collapsing of the channel banks immediately downstream from the structure. It was later determined that a local soil layer aggravated the bank caving at structure No. 5. This structure was chosen for the initial testing to determine appropriate modifications to minimize downstream scour. The modifications that were developed were specific to the 1 on 8 exit flare constructed at structures No. 5 through No. 12. Structure No. 2 was used to determine similar modifications for structures No. 1 through No. 4, which had exit flares of 1 on 4. Additional exit flares were tested using structure No. 2 as the base in order to determine the maximum flare where flow separation was not present.

A 1:16-scale model initially reproduced structure No. 5 which had the greatest amount of scour below the structure. Approximately 200 ft. of the trapezoidal channel upstream of the structure and approximately 500 ft. of downstream channel were reproduced. A moveable sand channel was used for the channel downstream of the grade control structure throughout the study.

The grade control structure (Figure 1a) consisted of a 36-ft-long approach transition section that reduced the base width of the channel from 54 ft. to 18 ft. The base of the approach transition section had



a. Structure No. 5



b. Structure No. 2

Figure 1. Original design.

a 1 on 2 flare and the side slopes transitioned from 1 on 3 to 1 on 2.5. The 18-ft-wide base width prismatic section remained constant for 308 ft. where the exit transition section began. The 144-ft-long exit transition section had a 1 on 8 base flare, and the side slopes transitioned back to the 1 on 3 side slopes. Graded riprap was used to form the grade control structure throughout the study. Riprap gradation A, as shown in Table 1, was used throughout the structure except for 50 ft. either side of the downstream end of the prismatic section (sta 684+56) where riprap gradation B was installed.

Table 1
Gradation for Rock Riprap, Structures No. 5-No. 12

Gradation	Stones, lb.	Cumulative Percent Lighter by Weight
A	225	100
	85	25-50
	10	5-20
B	1,200	100
	500	40-75
	300	25-50
	125	10-30
	30	0-10

NOTE: Spalls and rock dust that will pass a 3- in. sieve shall consist of less than 5 percent by weight.

After tests with structure No. 5 were completed, structure No. 2 was reproduced at a scale of 1:24 due to the larger size of this structure and the limits of the model facility. This structure was modeled to develop modifications to minimize scour below the existing structures No. 1 through No. 4 that have 1 on 4 exit flares. The modifications developed for structures No. 5 through No. 12 were for grade control structures having 1 on 8 exit flares. The model of structure No. 2 reproduced approximately 300 ft. of channel upstream and approximately 500 ft. downstream of the grade control structure. This structure is similar to structure No. 5 as shown in Figure 1b. Some of the differences are that the channel base is 80 ft. wide, the prismatic section is 29 ft. wide and contains a 3.7-ft. vertical drop within the 586-ft-long section, and that the exit flare is 1 on 4. Riprap gradation requirements for structure No. 2 are shown in Table 2.

Table 2
Gradation for Rock Riprap, Structures No. 1 - No. 4

Weight of Stones, lb.	Cumulative Percent Lighter by Weight
225	100
125	40-75
85	25-50
60	10-30
10	0

TESTS AND RESULTS

Structure No. 5

Structure No. 5 was designed to pass 2,335 cfs with the upstream and downstream flow depths being equal to 8.5 ft. Baseline flow conditions were determined for the design condition with the center- line water-surface profile shown in Figure 2a. As shown by the water-surface elevations, the flow line dropped through the converging approach as the flow accelerated. Backwater effects from the tailwater are evident in the downstream one-third of the prismatic section. Flow through the prismatic section separated from the side slopes at the upstream end of the exit transition for all flows. The flow separation caused eddies to form on both sides of the exit transition and downstream channel, concentrating the flow to the center of the channel. Velocity cross sections at several locations within and downstream of the structure are shown in Figure 2b. Flow separation is evident in Figure 2b at structure (sta 682+00). Scour tests were conducted using a synthetic hydrograph due to the absence of a design hydrograph. Test results indicated that significant scour of the

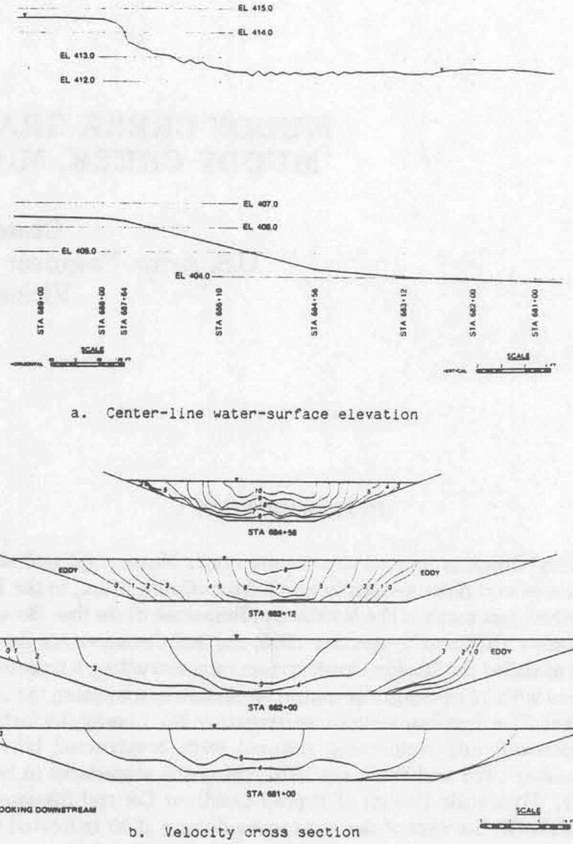


Figure 2. Structure No. 5, original design, discharge = 2,335 cfs, tailwater = 8.5 ft

channel invert occurred as the result of the flow concentration. Upstream flow depths were determined to be 8.2 ft. at the design flow. All subsequent testing was conducted with upstream and downstream depths equal.

In the type 2 design exit transition, a hump in the invert of the exit transition was tested to determine if this design would force the concentrated flow to spread over the width of the channel. In order to affect the concentrated flow, the hump had to break the water surface; otherwise the flow remained concentrated downstream of the structure. When the hump did break the water surface, the concentrated flow was split into two jets which scoured the channel invert on both sides of the downstream channel. This design was deemed unsatisfactory.

The type 3 design exit transition involved installing baffles in the exit transition by driving H- piles in the invert. Nominal 14-in. H-piles were arranged in various locations extending the full depth of design flow (8.2 ft.) above the channel invert. Test results indicated that the maximum effectiveness of the baffles was achieved when the downstream baffles intercepted the interference wake of the upstream baffles. These wakes are similar to the bow wakes of ships, and theoretical work by Kostyukov (reference 2) indicates that for the flow conditions at the exit transition the wake angle is approximately 19° 28'. Adjustments in the model for maximum interference resulted in a 17-degree angle for locating the downstream baffles. Single H-piles were tested as the type 3A design exit with minimal effect on the downstream scour. The type 3B design exit transition incorporated three H-piles at each location resulting in a substantial reduction in downstream scour. Due to the minimal amount of scour produced by the synthetic hydrograph, the testing procedure was changed to subjecting each design to the design flow of 2,335 cfs for a 24-hour period (prototype). The optimum baffle height was determined by testing the type 3B design baffles at heights of 4, 5, 6, and 8 ft. in the exit transition. Scour produced with the 6-ft. baffles was approximately the same as that produced with the 8-ft. baffles. Test results with the 5-ft. baffle were significantly worse than with the 6-ft. baffles, and the 4-ft. baffles provided the least improvement over the as-built design. Based on these results, a baffle height of 75 percent of the design depth was determined to be most effective. This resulted in a baffle height of 6.2 ft.

Additional baffle designs were tested to try to reduce the potential for the baffles to collect debris. The type 3C design baffles offset the outside H-piles in each baffle downstream such that the downstream flange of the center H-Piles was even with the upstream flange of the outside H-piles. Scour resulting from this design was approximately the same as with the type 3B design baffles for similar baffle heights. Type 3D design baffles incorporated baffles constructed with 2 H-piles placed adjacent to each other. This design did not perform as well as the type 3B or the type 3C design baffles. Nominal 12-in. H-piles were tested using the type 3B and 3C arrangements with inferior results. The type 3C design baffles were also modified by installing the center H-pile on a batter. This streamlining reduced the effectiveness of the baffles significantly.

From these tests it was determined that the type 3C design with the 6.2-ft-high baffles was the most effective design in reducing scour downstream of structure No. 5. The semiwedge shape of the baffles should reduce the amount of debris that collects on the baffles. Some debris should pass over the baffles during high-flow events. Centerline water-surface elevations and velocity cross sections with the design flow are shown in Figure 3.

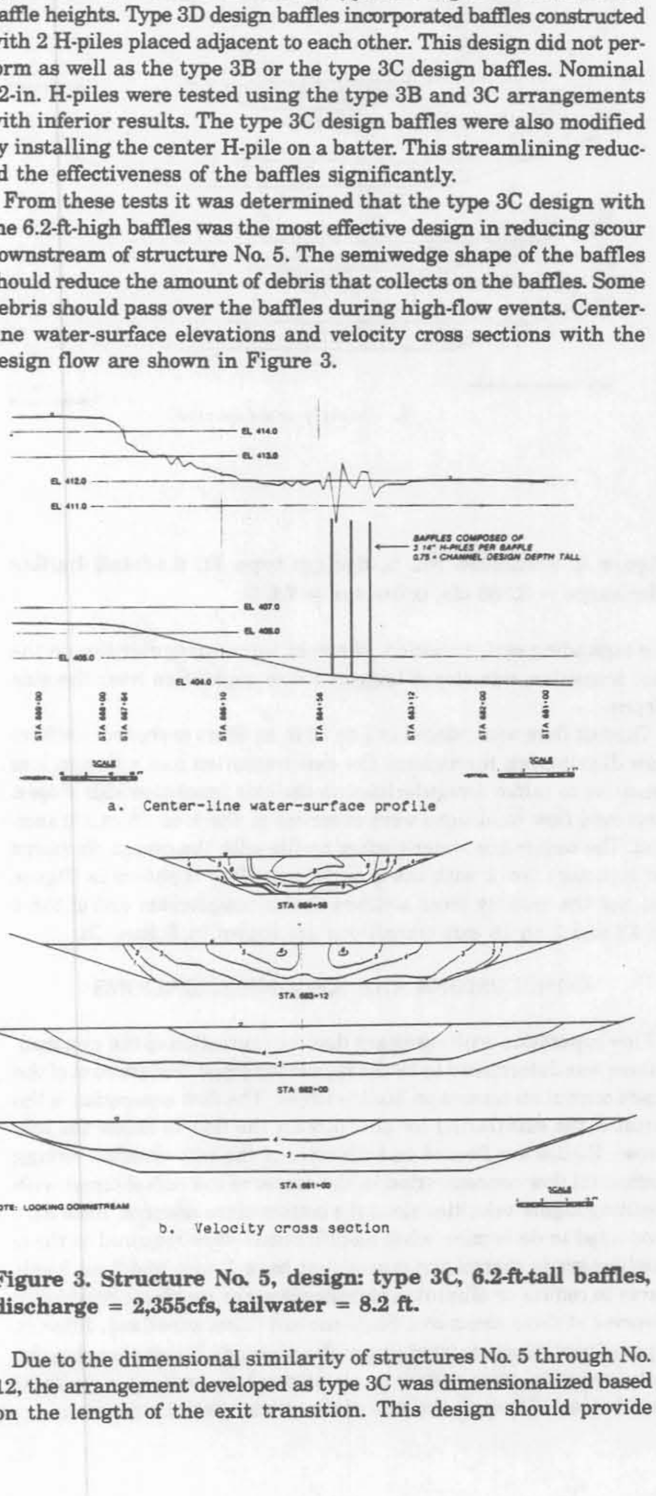


Figure 3. Structure No. 5, design: type 3C, 6.2-ft-tall baffles, discharge = 2,355cfs, tailwater = 8.2 ft.

Due to the dimensional similarity of structures No. 5 through No. 12, the arrangement developed as type 3C was dimensionalized based on the length of the exit transition. This design should provide acceptable flow conditions downstream of structures No. 5 through No. 12 and is shown in Figure 4a.

Structure No. 2

Flow conditions at structure No. 2 were similar to those observed at structure No. 5. Flow separation occurred at the upstream end of the exit transition, forming eddies on both sides of the outlet channel which concentrated the flow to the center of the channel. Stage-discharge relations indicated that the design flow resulted in an approach depth of 7.6 ft. instead of the 8.5 ft. used for the design. Consequently, the design tailwater depth that was used for the model tests was 7.6 ft. The water-surface profile and velocity cross sections for the as-built condition are shown in Figure 5. Concentration of the flow to the center of the exit channel is clearly shown at sta 425+00 and 424+00 on Figure 5b.

The baffle pattern developed for the 1 on 8 exit flare for grade control structures No. 5 through No. 12 was tested in structure No. 2 with the 1 on 4 exit flare and found to be inadequate. Each row of baffles had one additional baffle added to each end because of the wider flare. Test results indicated that a small portion of the flow concentrated to each side of the exit flare between the side slopes and the baffles causing excessive scour on the sides of the channel downstream of the riprap structure.

Two additional baffles were added to the fourth row in an attempt to reduce the velocities along the sides of the channel. Little improvement was achieved with this modification. The end baffle blocks on the fourth row were moved 3.5 ft. toward the side slopes in an effort to further reduce the velocities along the sides of the channel. Again,

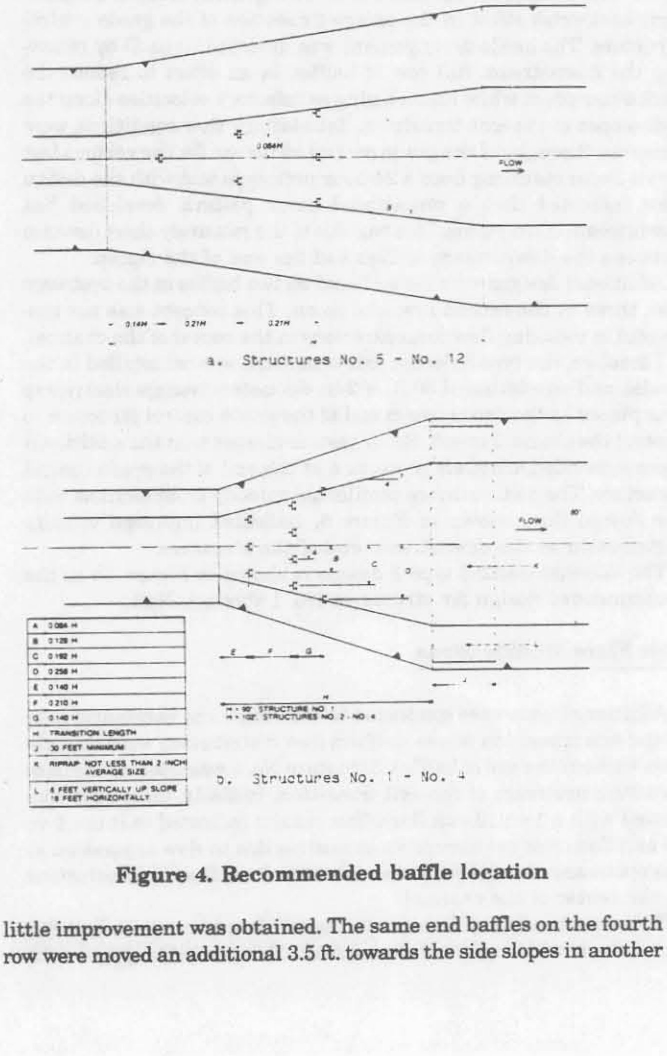


Figure 4. Recommended baffle location

little improvement was obtained. The same end baffles on the fourth row were moved an additional 3.5 ft. towards the side slopes in another

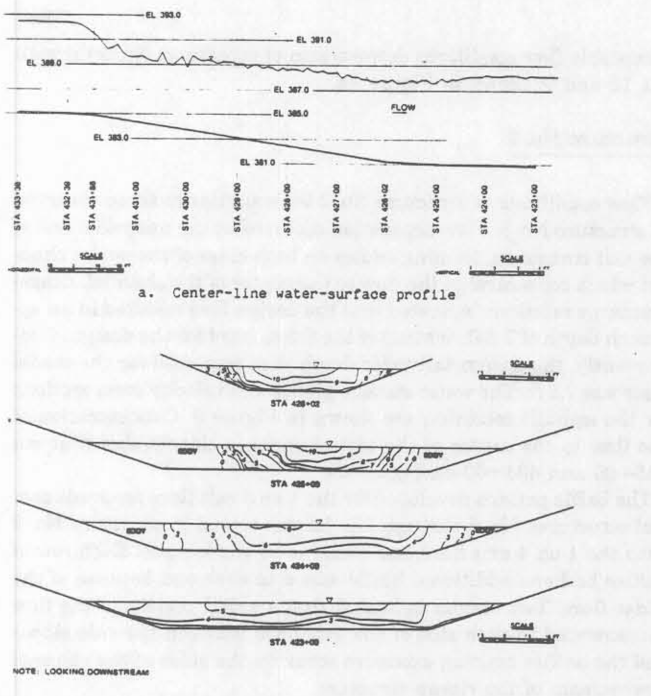


Figure 5. Structure No. 2, original design, discharge = 3,166 cfs tailwater = 7.6 ft.

attempt to reduce the velocities along the sides of the channel. This design was successful in reducing flow concentrations along the sides of the exit transition, but this baffle arrangement created a significant backwater effect in the prismatic section of the grade control structure. The baffle arrangement was modified (type 8) by removing the downstream full row of baffles in an effort to reduce the backwater effect while maintaining satisfactory velocities along the side slopes of the exit transition. Satisfactory flow conditions were observed throughout the grade control structure for the various test flows. Scour resulting from a 24-hour prototype test with the design flow indicated that a pronounced scour pattern developed just downstream of the riprap. This was due to the relatively short distance between the downstream baffles and the end of the riprap.

Additional designs were tested based on two baffles in the upstream row, three in the second row, and so on. This concept was not successful in reducing flow concentrations in the center of the channel.

Therefore, the type 8 design exit transition was reinstalled in the model, and an additional 30 ft. of 2-in.-diameter (average size) riprap was placed at the downstream end of the grade control structure to protect the channel invert. Scour tests indicated that the additional riprap provided adequate protection at the end of the grade control structure. The water-surface profile and velocity cross sections with the design flow, shown in Figure 6, indicated improved velocity distribution at the downstream end of the structure.

The dimensionalized type 8 design is shown in Figure 4b as the recommended design for structures No. 1 through No.4.

Exit Flare Modifications

Additional tests were conducted to determine the maximum flare in the exit transition where uniform flow distribution would be present without the use of baffles. Structure No. 2 was used as the base structure upstream of the exit transition. Initially, tests were conducted with a 1 on 10 exit flare. Test results indicated that the 1 on 10 exit flare was too abrupt an expansion due to flow separation at the upstream end of the exit flare and resulting flow concentrations in the center of the channel.

Tests were conducted with the exit flare reduced to 1 on 12. Satisfactory flow conditions were observed as the flow tended to spread with

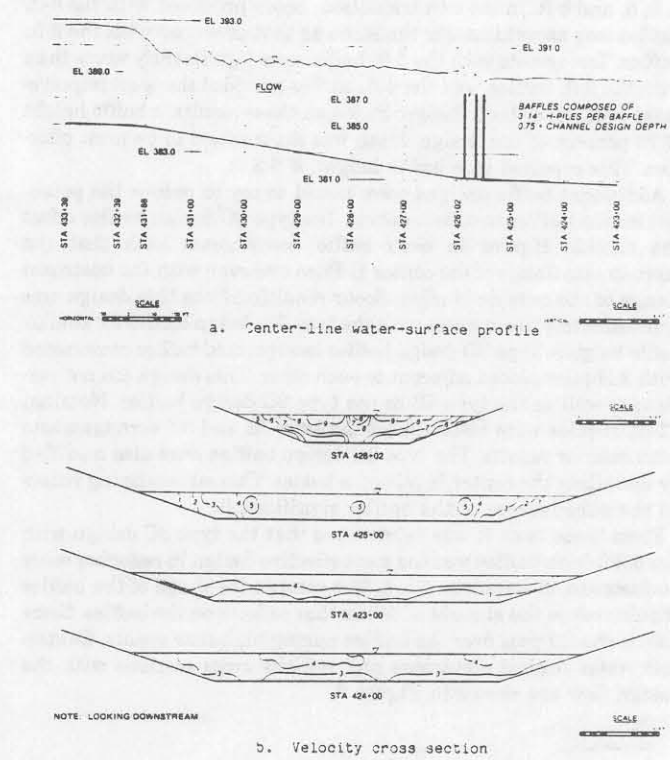


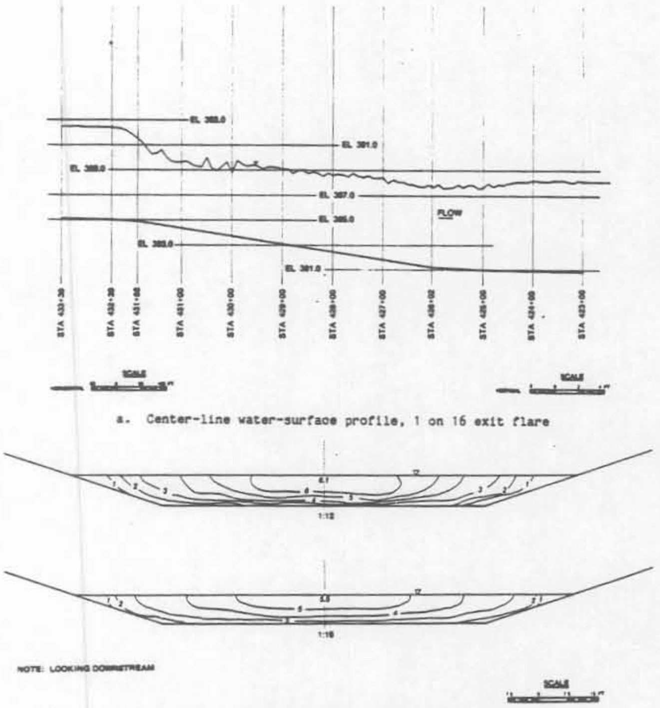
Figure 6. Structure No. 2, design: type 11, 6.4-ft-tall baffles discharge = 3,166 cfs, tailwater = 7.6 ft.

the expanding exit transition. However, minor irregularities on the exit transition side slopes triggered flow separation near the side slopes.

The exit flare was reduced to 1 on 16 in an effort to produce uniform flow distribution throughout the exit transition and a design less sensitive to minor irregularities on the exit transition side slopes. Improved flow conditions were observed in the 1 on 16 exit transition. The center-line water-surface profile with the design discharge for structure No. 2 with the 1 on 16 exit flare is shown in Figure 7a, and the velocity cross sections at the downstream end of the 1 on 12 and 1 on 16 exit transitions are shown in Figure 7b.

CONCLUSIONS AND RECOMMENDATIONS

Flow separation with resultant flow concentration in the exit transitions was determined to be the reason for scour downstream of the grade control structures on Muddy Creek. The flow separation is the result of the exit flaring too abruptly for the flow to follow the side slopes. Eddies are formed on both sides of the exit channel, forcing additional flow concentration in the center of the exit channel with resulting higher velocities along the bottom of the channel. Tests were conducted to determine what modifications were required to these existing grade control structures that have 1 on 4 and 1 on 8 exit flares to reduce or eliminate significant scour problems previously observed at these structures. Since the exit flares were fixed, different types of modifications involving baffle piers or a hump placed in the exit transition were tested in an attempt to produce a uniform distribution of flow at the end of the grade control structure.



a. Center-line water-surface profile, 1 on 16 exit flare

b. Exit velocity cross sections, 1 on 12 and 1 on 16 exit flare

Figure 7. Exit flare modifications, discharge = 3,166 cfs tailwater = 7.6 ft.

Test results indicated that a baffle arrangement with the height of the baffle piers being 75 percent of the design depth was the most effective design in producing a uniform distribution of flow in the exit channel without any significant backwater effect in the grade control structure.

For this type of grade control structure without the use of baffles, test results indicated that flow separation occurred at the upstream end of the exit transition if the exit flare was greater than a 1 on 12 ratio. Minor irregularities (differential settlement or vegetation) on the side slopes of a 1 on 12 flare caused separation and flow concentration, indicating that this was approximately the critical flare ratio below which incipient flow separation occurs. Additional tests indicated that the 1 on 16 exit flare was the maximum that provided satisfactory flow conditions without being sensitive to minor irregularities on the side slopes, and therefore was the recommended design.

PROTOTYPE RESULTS

The recommended baffle designs were installed in the Muddy Creek System in 1986. Subsequently, flow depths approximately equal to the baffle heights have been observed by SCS personnel and appear to substantiate the model results. The waves formed by the baffles are intercepted by the next baffle downstream and wave heights are reduced by each succeeding row of baffles. Flow moves downstream across the full width of the channel.

ACKNOWLEDGMENT

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REFERENCE

1. US Department of Agriculture, Soil Conservation Service. 1976 (Jan). "Hydraulic Design of Riprap Gradient Control Structures," Technical Release No. 59, Washington, D.C.
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