FLOOD CONTROL STRUCTURES RESEARCH PROGRAM

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ANNOTATED BIBLIOGRAPHY ON GRADE CONTROL STRUCTURES

by

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13. ABSTRACT *(Maximum 200 words)*

Grade control structures (GCS) are an important facet of the broad effort directed at controlling erosion in flood-control channels that have erodible bed and banks. The annotated bibliography describes published studies of numerous hydraulic structures that have been studied and used for grade control. The bibliography contains 112 citations in addition to a brief discussion of published information available to the GCS designer.

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PREFACE

This annotated bibliography was authorized under the Flood Control Structures Research Program sponsored by the Headquarters, US Army Corps of Engineers (HQUSACE), under Work Unit No. 32507, "Grade Control and Drop Structures." Messrs. Tom Munsey and Sam Powell were HQUSACE Technical Monitors.

The study was conducted during the period October 1988-October 1990 at the US Army Engineer Waterways Experiment Station (WES) Hydraulics Laboratory (HL) under the direction of Messrs. Frank A. Herrmann, Jr., Chief, HL, and Richard A. Sager, Assistant Chief, HL, and under the general supervision of Mr. Glenn A. Pickering, Chief, Structures Division (SD), HL, and Dr. Bobby J. Brown, Chief, Hydraulic Analysis Branch (HAB), SD. The literature survey was conducted by Dr. Frank M. Neilson and Mr. Terry N. Waller, HAB, and Mrs. Katherine M. Kennedy of the Information Technology Laboratory (ITL), WES. This bibliography was edited by Mrs. Marsha C. Gay, ITL.

Commander and Director of WES during preparation of this report was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

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ANNOTATED BIBLIOGRAPHY ON GRADE CONTROL STRUCTURES

PART I: INTRODUCTION

1. This bibliography is one milestone of a research effort directed toward developing guidance for the selection and design of grade control structures. It includes structures that have been studied either in the field or in the laboratory and that have been described in the technical literature. The specific concerns are the hydraulic design, characteristics, and performance of grade control structures including the following:

- a. Design details.
- b. Discharge ratings (as needed to define water-surface profiles for channel design).
- c Energy dissipation (as needed to determine bank protection needs downstream of a structure).
- d. Local scour protection.
- e. Sediment flow-through capability (as needed to evaluate the overall impact on channel bed and banks and on channel capacity).
- f. Maintenance and debris management concerns.

2. Grade control is an important part of stable flood-control channel design (McCarley et al. 1990). Present design guidance regarding grade control structures is from diverse sources. Specific topics require both extensive literature and experimental study prior to field implementation. Research needs were identified by McCarley et al. (1990) during a survey of US Army Corps of Engineer (USACE) District and Division offices. These needs adequately define broad problem areas that are lacking in design guidance. This grade control work unit was subsequently initiated within the Flood Control Structures Research Program of the US Army Corps of Engineers Civil Works Research and Development Program.

3. Different terminology and symbols are used by different authors. For this bibliography, structure geometry and hydraulic performance are described in terms that are in general agreement with USACE practice. The following Federal agencies, laboratories, and organizations are commonly referred to by acronym:

Acronym	Organization
ARS	Agricultural Research Service, US Department of Agriculture
ASCE	American Society of Civil Engineers
USACE	US Army Corps of Engineers
SCS	Soil Conservation Service, US Department of Agriculture
USBR	Bureau of Reclamation, US Department of the Interior
USDA	US Department of Agriculture
USGS	US Geological Survey
WES	US Army Engineer Waterways Experiment Station

4. Two recent reviews of grade control structure literature and design practice are included in this bibliography. These reviews are particularly notable:

a. Nakato (1989) extends citations into foreign grade control structure design practice.

b. McLaughlin (1986) includes various types of rock structures.

PART II: BACKGROUND

5. The boundaries of streams change over time as a function of numerous environmental factors. Natural processes and man-induced changes in a system can cause lowering of the streambed (termed degradation), which is accompanied by changes in cross-sectional shape and in alignment. Other factors can raise the streambed (termed aggradation), which also causes changes in the channel geometry. Hydrologic and land-use seasonal variations enter into the quantities of sediment and water moved by a stream. For smaller streams with highly erodible boundaries, a continuously changing channel is to be expected.

6. Bank erosion resulting from channel shape changes alters environmental conditions as well as having the potential to cause significant economic loss. The rate of change is most rapid whenever the rate at which material is eroded and removed is much greater or much less than the rate at which material is deposited.

7. Citations that discuss bank and bed erosion in the context of grade control structure information are included in this bibliography. Otherwise, the need for sedimentation studies for erodible reaches is discussed, and references are provided, in other USACE documents. For example, sedimentation study methods are described in the following manual:

> US Army Corps of Engineers. 1989. "Sedimentation Investigations of Rivers and Reservoirs," EM 1110-2-4000, USACE Publications Depot, Hyattsville, MD.

8. One natural factor that limits the tendency of a stream to migrate is geologic hard points. These hard points are erosion-resistant strata that tend to hold, at least temporarily, the channel bed and banks in position. For example, bank height, which is one measure of bank stability, tends to be limited by the presence of hard points.

9. The hydraulic structure that is similar to an enhanced geologic hard point is termed a grade control structure. The term grade is used to describe either (a) the average gradient of the streambed or (b) the slope of the energy grade line. Most often, a series of grade control structures is used. Several small drops, rather than one large structure, tend to smooth both gradients while avoiding severe local effects.

10. The effects of hydrology, land use, geology, and other regional

factors are evaluated by models of the fluvial process to determine (a) locations requiring grade control, (b) stage-discharge needs at the control, and (c) the crest elevation for the grade control structure. The models are computer-based and address first the stream hydrographs (HEC-2, for example) and then the sediment routing problem (TABS-2, for example). The sediment transport process is modified by the structure so that both preproject and postproject sedimentation studies are needed. The parameters and the decision process used to set the spacing and drop for a grade control structure are therefore complex and important parallel study topics.

11. Information regarding computer-based models of the sedimentation process are not included in this bibliography unless in a citation otherwise containing grade control structure information.

12. Other terms have been used in place of "grade control structure." Department of Agriculture studies (Woolhiser and Lenz 1965) mention "gully control" structures, for example. USACE practice (USACE 1970) has been to consider "sediment control" structures in three categories:

- a. Stabilizers have crests or low sills near bed level. Stabilizers are designed to retain existing bed and energy grade lines.
- b. Drop structures are shaped similarly to free overfalls. These structures provide an energy loss while passing sediment and debris.
- c. Debris basins and check dams have crests extending above the bed. These structures retard the approaching flow for sediment deposition and retention purposes.

13. The fundamental constraints to structure selection are as follows:

- a. Economics. Basinwide benefits, for example, flood control or bank protection, are economic factors that initially determine the need for upgrading a stream. A great latitude exists as far as materials and construction methods for grade control structures are concerned. For smaller streams, significant savings are obtained by selecting a structure that is locally inexpensive, provided the structure is durable and of low maintenance and meets other design constraints.
- b. Environmental. The relationships between a watershed and the concurrent range of dependent environmental factors are affected by the design of the grade control structure. Significant differences in environmental impact can be obtained by altering stage-discharge or sediment retention characteristics, as examples, in the structure selection and design process.

14. Design parameters, as listed by Goitom and Zeller (1989) for soil-cement structures, include the following topics:

Typical Hydrograph	Land Cost and Use
Velocity Range	Aesthetics
Discharge Range	Safety
Flow Duration	Construction Material
Low Flow Conditions	Construction Costs
Scour Potential	Maintenance
Aggradation Potential	

15. The sedimentation evaluation (scour and aggradation, above) determines the spacing between structures along a stream and the drop height for each structure. Bank and bed protection methods near a particular type of grade control structure are usually included in a documented description of the structure. However, the overall stream channel sedimentation evaluation is only rarely included and is not directly addressed in this bibliography. The Goitom and Zeller document, which does include channel sedimentation, outlines the following study topics:

a. Determine the dominant discharge.

b. Determine the hydraulic parameters for the dominant discharge.

c. Determine the characteristics of the streambed sediments.

d. Determine if armoring potential exists at dominant discharge.

e. Select appropriate sediment-transport relationship.

f. Estimate the long-term sediment supply at dominant discharge that is expected to be delivered to the reach under future watershed conditions.

g. Compute the sediment-transport capacity of the study reach at dominant discharge.

h. If supply is equal to capacity, then adjust the channel slope to obtain an equilibrium slope for which supply is equal to capacity at dominant discharge or armoring controls.

i. Using the equilibrium slope, compute the spacing of the grade control structures (based on equilibrium slope, actual channel slope, and drop height).

j. Using an appropriate formula, compute the expected streambed scour downstream of the grade control structure.

k. Bury invert of the grade control below the expected scour depth.

16. A structure may be designed either uniquely for grade control or to provide grade control in conjunction with an alternate primary function. Most citations herein deal with a single type of structure as noted in the annotations. Citations having design guidance applications for larger agencies usually discuss several types of structures. For example, a survey of structures presently used in the Denver, CO, area (McLaughlin Water Engineers,

Ltd., 1986) includes the following types:

Type of Structure	Number of Cases
Baffled apron drops	5
Vertical drop with loose riprap basin	5
Vertical drop with hard basin	14
Sloping rock drops	12
Sloping grouted rock	7
Sloping concrete drops and other hard basins	4
Low-flow erosion checks and control measures	5

17. USACE guidance (1970) includes a discussion of three types of sediment control situations that enter into the selection of type of structure:

a. Stabilizers are designed to limit channel degradation. Two structural designs, a rock stabilizer and a sheet piling stabilizer, are provided.

b. Drop structures are designed to reduce channel slopes to effect nonscouring velocities. Details and design charts for a typical drop structure are included.

c. Debris basins and check dams are built in the headwaters of flood control channels having severe upstream erosion problems in order to trap large bed-load debris before it enters main channels. A typical design, including both a spillway and a pool drain, of a debris basin is included.

18. The Bureau of Reclamation design guidance for hydraulic structures (1978a, 1978b, 1987) provides details for a broad range of structures. Most of these structures are viable options for grade control applications in particular field situations.

PART III: SUMMARY

19. The bibliography provides information sources applicable to matching design options to diverse functional needs. Many types of structures have been tested in practice and in the laboratory. The definition of function in terms of sedimentation issues such as degradation and aggradation is not adequately addressed in the citations. Since these issues impact directly on structure height and spacing, further research, for the benefit of providing comprehensive design guidance to the overall grade control problem, appears necessary.

PART IV: ANNOTATED BIBLIOGRAPHY

A

1. Ables, Jackson H., Jr. 1976. "Divide Cut Drainage Structures, Tennessee-Tombigbee Waterway, Mississippi and Alabama; Hydraulic Model Investigation," Technical Report H-76-18, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

   Standardized designs for drainage structures in the Divide Cut Section of the Tennessee-Tombigbee Waterway were developed in model tests conducted on the USBR type VI impact basin at a scale of 1:4, on the minor drainage chutes and energy dissipators at a scale of 1:10, and on the major drainage structures at a scale of 1:25. Test results indicate that the type VI impact basin performs satisfactorily below rectangular channels for all discharges tested, and critical dimensions are tabulated for discharges expected at drainage structures where the type VI basin will be installed. Generalized information was developed to permit satisfactory design of minor drainage chutes and energy dissipators emptying into the canal. A satisfactory baffled chute spillway was developed for the largest of the drainage structures. Model test results will permit design of the other three major structures based on a unit discharge of 60 cfs common to the five structures for 100-year frequency flows.

2. Ables, Jackson H., Jr., and Boyd, Marden B. 1969. "Low-Water Weirs on Boeuf and Tensas Rivers, Bayou Macon, and Big and Colewa Creeks, Arkansas and Louisiana; Hydraulic Model Investigation," Technical Report H-69-13, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

   A 1:20-scale model reproducing one-half of the channel section through a low-water weir was used to test eight plans of channel improvement. The tests were conducted with a drop height of 5.5 ft, and discharges up to 10,000 cfs were observed. Flow conditions and slope protection downstream from the weir to control the flanking problem were found to be satisfactory with channel improvement plans 6 and 8. Riprap with an average weight of 33 lb was used in slope protection in both plans. A model headwater-tailwater rating curve was obtained. A second 1:20-scale section model was constructed in a 2.5-ft-wide glass flume for more generalized riprap tests in the vicinity of the structure. Several drop structure plans were observed to develop an effective, economical drop structure. Of primary concern were development of some of the dimensions of various elements of the structure and determination of riprap requirements in the vicinity of the structure. Limiting tailwater curves for 220- and 325-lb riprap are furnished as a guide in riprap selection at drop structures with drop heights of from 5 to 10 ft. Suggestions as to the use of these curves also are included. A basin length of 20 ft is considered to be adequate at projects where the jet will ride through at unit discharges exceeding about 10 cfs. A riprap plan which provides additional protection to the structure is presented in Appendix A.

3. Ables, Jackson H., Jr., and Pickering, Glenn A. 1975. "Flood Control Project on Lytle and Warm Creeks and Santa Ana River, California; Hydraulic Model Investigation," Technical Report H-75-7, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

The Lytle and Warm Creeks and Santa Ana River project will provide another important unit under the general comprehensive plan for flood control in San Bernardino County, California. The proposed plan for containing the flood flows will consist of raising levees; excavating streambeds; and constructing grade control structures, energy dissipators, bridges, and several thousand feet of high-velocity concrete channels. The investigation was conducted on a 1:60-scale model that reproduced approximately 10,000 ft of the Santa Ana River, 600 ft of East Twin Creek, and 5,300 ft of Warm Creek. The existing and proposed bridges, concrete channels, and natural streambed channels with revetted slopes were also reproduced in the model. Tests were concerned with flow conditions; water-surface elevations; riprap stability; and sediment transport at the grade control structures, bridges, confluences, and energy dissipators.

4. Ackers, P., White, W. R., Perkins, J. A., and Harrison, A. J. M. 1978. Weirs and Flumes for Flow Measurement, Wiley, New York.

This book covers both theoretical and practical aspects of water measurement using gaging structures. Its scope covers small discharges in laboratories and processing plants, as well as those larger discharges in rivers that remain amenable to measurement by this technique. The conditions under which weirs and flumes are likely to provide an appropriate method and standard of accuracy are described, and the criteria for selecting a suitable structure are explained. (193 references)

5. Agostini, R., Bizzarri, A., Masetti, M., and Papetti, A. 1988. "Flexible Gabion and Reno Mattress Structures in River and Stream Training Works; Volume 1: Weirs," Maccaferri Gabions, Inc., Williamsport, MD.

Contents: Chapter I: Training and Hydraulic Protection Structures; Chapter II: Gabion Weirs; Chapter III: Design Criteria for Vertical and Stepped Weirs: Construction Details; Chapter IV: Design Criteria for Sloped Weirs: Construction Details; Chapter V: Examples of Calculations; Chapter VI: Examples of Completed Works. (66 references)

B

6. Blaisdell, F. W., and Donnelly, C. A. 1951. "Capacity of Box Inlet Drop Spillways under Free and Submerged Flow Conditions," Technical Paper No. 7, Series B, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis, MN.

This paper presents methods for determining free flow capacity; tests and results; illustrated description of test apparatus; effects of position of dike, approach channel width, and shape of inlet; and correction factors.

7. Blaisdell, F. W., and Donnelly, C. A. 1966. "Hydraulic Design of the Box-Inlet Drop Spillway," Agriculture Handbook No. 301, US Department of Agriculture, Agricultural Research Service, Washington, DC. Also published in 1951 as Technical Paper No. 8, Series B, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis, MN.

   The study resulted in the development of a generalized method for determining the free flow capacity of box inlet drop spillways. The procedure is outlined in this report. No practical generalized method for the determination of the submerged flow capacity was found; the submerged flow capacity is determined by a process of interpolation utilizing submergence curves obtained for a wide range of pertinent variables for this purpose.

8. Blaisdell, Fred W., Hayward, Kenneth M., and Anderson, Clayton L. 1982. "Model-Prototype Scour at Yocona Drop Structure," Proceedings of the Conference Applying Research to Hydraulic Practice, Jackson, MS, August 17-20, 1982, ASCE, Peter E. Smith, ed., pp 1-9.

   The scour measured at the exit of a straight drop spillway stilling basin model and the scour measured at its prototype are compared. There are three major parts to the paper: (1) features of the stilling basin design and its performance are presented; (2) the Yocona River prototype structure is described; and (3) a comparison of the model and prototype scour patterns concludes the presentation. (2 references)

9. Bormann, Noel Ernest. 1988. "Equilibrium Local Scour Depth Downstream of Grade-Control Structures," Ph.D. dissertation, Colorado State University, Fort Collins, CO.

   A theoretical analysis of the diffusion and path of two-dimensional jets is combined with particle stability analysis so that local scour from a variety of conditions can be described using two parameters. The geometry of the flow and structure is described by the impingement angle at the boundary. Separate empirical relationships are developed to estimate impingement angle for free jets and submerged jets. Local scour dynamics are described by a scour stability parameter which is a ratio of the force of the diffused jet velocity causing scour to the gravitational force resisting scour.

   To confirm the theoretical analysis, an extensive, large-scale experimental program was completed using unit discharge rates of up to 25 cfs/ft. The data collected are unique in three respects: (1) provide near-prototype-scale experimental local scour data; (2) test various face slopes of structures; and (3) test partially submerged flow conditions. The data collected are combined with four data sets available in the literature to represent a variety of flow and geometric conditions.

A sensitivity analysis of the predictive equations for local scour depth illustrates the disproportionately large effect small errors in values of the variables describing local scour have on predictions. This sensitivity is reflected in the large experimental scatter present in all local scour data.

10. Bos, M. G., ed. 1976. "Discharge Measurement Structures," Publication 20, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

This report presents instructions, standards, and procedures for the selection, design, and use of structures which measure or regulate the flow rate in open channels. The topics discussed cover lists of principal symbols, auxiliary weirs, sharp-crested weirs, short-crested weirs, flumes, orifices, miscellaneous structures, basic equations of motion in fluid mechanics, the overall accuracy of the measurement of flow, side weirs and oblique weirs, and suitable stilling basins. (173 references)

11. Brevard, John A. 1971. "Criteria for the Hydraulic Design of Impact Basins Associated with Full Flow in Pipe Conduits" (see complete citation under US Department of Agriculture).

12. Brevard, John A. 1975. "Hydraulic Design of Riprap Structure for Channel Gradient Control," paper presented at 68th Annual Meeting of the American Society of Agricultural Engineers, University of California, Davis, CA, June 22-25, 1975, Paper No. 75-2022, American Society of Agriculture Engineers, St. Joseph, MI.

Some channels can be stabilized economically using a riprap gradient control structure. The riprap structure consists of a prismatic channel with a transition at each end. For the design discharge, the riprap structure is designed to maintain a constant specific energy head through the structure. (4 references)

13. Bureau of Reclamation. 1978a. <u>Design of Small Canal Structures</u>, Denver, CO.

Contents: Chapter I: General Requirements and Design Considerations (9 refs); Chapter II: Conveyance Structures (14 refs); Chapter III: Regulating Structures (3 refs); Chapter IV: Protective Structures (11 refs); Chapter V: Water Measurement Structures (5 refs); Chapter VI: Energy Dissipators (10 refs); Chapter VII: Transitions and Erosion Protection (1 ref); Chapter VIII: Pipe and Pipe Appurtenances (12 refs); Chapter IX: Safety (3 refs); Appendix A: Glossary of Terms; Appendix B: Conversion Factors; Appendix C: Computer Program.

14. Bureau of Reclamation. 1978b. "Hydraulic Design of Stilling Basins and Energy Dissipators," Engineering Monograph No. 25, Denver, CO.

Contents: Section 1: General Investigation of the Hydraulic Jump on Horizontal Aprons (Basin I); Section 2: Stilling Basin for High Dam and Earth Dam Spillways and Large Canal Structures (Basin II);

Section 3: Short Stilling Basin for Canal Structures, Small Outlet Works, and Small Spillways (Basin III); Section 4: Stilling Basin Design and Wave Suppressors for Canal Structures, Outlet Works and Diversion Dam (Basin IV); Section 5: Stilling Basin with Sloping Apron (Basin V); Section 6: Stilling Basin for Pipe or Open Channel Outlets (Basin VI); Section 7: Slotted and Solid Buckets for High, Medium, and Low Dam Spillways (Basin VII); Section 8: Hydraulic Design of Hollow-Jet Valve Stilling Basins (Basin VIII); Section 9: Baffled Apron for Canal or Spillway Drops (Basin IX); Section 10: Improved Tunnel Spillway Flip Buckets (Basin X); Section 11: Size of Riprap to be Used Downstream from Stilling Basins. (75 references)

15. Bureau of Reclamation 1987. Design of Small Dams, Denver, CO.

Contents: Chapter 1: Plan Formulation; Chapter 2: Ecological and Environmental Considerations (31 refs); Chapter 3: Flood Hydrology Studies (9 refs); Chapter 4: Selection of Type of Dam; Chapter 5: Foundations and Construction Materials (28 refs); Chapter 6: Earthfill Dams (72 refs); Chapter 7: Rockfill Dams (47 refs); Chapter 8: Concrete Gravity Dams (14 refs); Chapter 9: Spillways (31 refs); Chapter 10: Outlet Works (15 refs); Chapter 11: Diversion During Construction (1 ref); Chapter 12: Operation and Maintenance (2 refs); Chapter 13: Dam Safety (21 refs); Appendix A: Reservoir Sedimentation (41 refs); Appendix B: Hydraulic Computations (11 refs); Appendix C: Structural Design Data (13 refs); Appendix D: Soil Mechanics Nomenclature; Appendix E: Construction of Embankments (8 refs); Appendix F: Concrete in Construction (6 refs); Appendix G: Sample Specifications (4 refs); Appendix H: Typical Checklist of Dams and Structures for On-site Inspection; Appendix I: Conversion Factors.

C

16. Colyer, S. 1987. "Fishing the Four-Lane," Civil Engineering, Vol 47, No. 8, pp 50-51.

Recent changes in one Montana canyon have shown that highways and freshwater fish can coexist. Twenty years ago, the Montana Department of Highways began plans to construct one of Interstate 15's final stretches. To preserve the habitat of the native trout and whitefish, engineers took a number of measures to maintain existing fish cover by building shore-anchored structures and planting them with new grasses and shrubs. Artificial rock drop structures, sunken cover, and log check dams were also used to create new fish holding areas. Erosion control structures were also built.

17. Cooper, C. M., and Knight, S. S. 1987. "Fisheries in Man-Made Pools Below Grade-Control Structures and in Naturally Occurring Scour Holes of Unstable Streams," Journal of Soil and Water Conservation, Vol 42, No. 5, pp 370-373.

As part of the ecological research on high-gradient streams in the Yazoo River Basin of Mississippi, four man-made pools below grade control (low-drop) structures and four naturally occurring scour-hole pools were sampled for fish composition by the rotenone method. Tillatoba and Long Creeks were chosen because of the presence of grade control structures used as structural management practices for control of channel erosion from headcutting and because the region has been included in a comprehensive land treatment and channel stability project. Differences in the fisheries characteristics of the two pool habitats were expected because of differences in their relative stability, bottom substrate, and pool life expectancy. Natural scour holes yielded 0.06 kg/cu m of fish from 39 species; 0.018 kg/cu m were considered harvestable. Twenty-nine species in man-made pools yielded 0.06 kg/cu m with 0.025 kg/cu m being harvestable. Length frequency distribution indicated that there was better growth of many species and more stable reproducing populations of forage fish in man-made pools, although they yielded somewhat fewer species. Drop structure pools have several advantages over most natural scour holes in their fisheries characteristics as well as providing protection from stream channel degradation. (5 references)

18. Corry, M. L., Thompson, P. L., Watts, F. J., Jones, J. S., and Richards, D. L. 1983. "Hydraulic Design of Energy Dissipators for Culverts and Channels," Report No. FHWA/EPD-86/110, HEC-14, Federal Highway Administration, Washington, DC.

The manual provides information for designing energy dissipators for culvert outlets and for drops in open channels. Design procedures and charts are provided for selecting and sizing impact basins, hydraulic jump basins, riprap basins, and drop structures. The basic hydraulic design concepts for energy dissipation are presented, and application of these concepts to the design of various types of basins is illustrated through the use of example problems.

D

19. DeCoursey, D. G. 1981. "Stream Channel Stability; Comprehensive Report: Project Objectives 1 thru 5," prepared for US Army Corps of Engineers, Vicksburg District, Vicksburg, MS, under Section 32 Program, Work Unit 7, USDA-ARS National Sedimentation Laboratory, Oxford, MS.

This volume was written to describe how to carry out an analysis of a channel stability problem. Detailed reports of the various research projects associated with channel stability problems in the Yazoo River Basin are presented as appendices. The overall research program had five major objectives: (1) determining the influence of grade control structures on channel stability; (2) monitoring the performance of selected channel stabilization methods; (3) evaluating the effects of geology, geomorphology, soils, land use, and climate on runoff and sediment production from major source areas; (4) estimating the water and sediment production from a large, mixed-land-use watershed and the

integrated effects on channel stability; and (5) evaluating the relation between valley stratigraphy and channel morphology and their combined effects on channel stability. (125 references)

20. Denzel, Charles W., and Strauser, Claude N. 1982. "Kaskaskia River Grade Control Structure," Proceedings, 1982 International Symposium on Urban Hydrology, Hydraulics and Sediment Control, Lexington, KY, July 27-29, 1982, University of Kentucky, Water Resources Research Institute, pp 135-139.

The Kaskaskia River control structure is located near the US Highway 460 bridge at Fayetteville in St. Clair County, Illinois. Since the completion of the navigation channel in 1972 from Fayetteville to the confluence with the Mississippi River, some 36 canal miles, headcutting and channel widening have occurred upstream of Fayetteville. Downstream of Fayetteville, about 2.5 million cubic yards of sediment have been deposited in the upper 6 miles of the navigation canal. A grade control structure is required so that upstream headcutting and downstream sedimentation are minimized. The design of the structure was based on theoretical computations and verified by model test at the US Army Engineer Waterways Experiment Station. It is concluded that a structure is needed in order to maintain the upstream water surface profile so as not to disturb the state of dynamic equilibrium which presently exists in the channel, both upstream and downstream of Fayetteville. (1 reference)

21. Donnelly, Charles A., and Blaisdell, Fred W. 1954. "Straight Drop Spillway Stilling Basin," Technical Paper No. 15, Series B, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis, MN. Also published in Journal of the Hydraulics Division, ASCE, Vol 91, No. HY3, pp 101-131.

This paper describes the development of generalized design rules for a stilling basin for use with the straight drop spillway. This stilling basin design was developed because experience in the field had shown that there was no satisfactory stilling basin for the straight drop spillway. Limited field experience indicates that the design adequately protects the downstream channel from scour.

Water falling over the spillway crest falls onto a flat apron. The nappe is broken up by floor blocks, which also prevent damaging scour of the downstream channel banks. An end sill prevents scour of the downstream channel bed. Flaring wing walls, triangular in elevation, prevent erosion of the dam fill. For proper operation of the stilling basin, the contraction of the flow at the ends of the spillway opening must be partially suppressed.

An important finding is that the stilling basin length computed for the minimum tailwater level required for good performance may be inadequate at higher tailwater levels. Dangerous scour of the downstream channel may occur if the nappe is supported sufficiently by high tailwater so that it lands beyond the end of the stilling basin. A method of computing the stilling basin length for all tailwater levels is presented. (9 references)

E

22. El Khashab, A. M. 1986. "Form Drag Resistance of Two-Dimensional Stepped Steep Open Channels," Canadian Journal of Civil Engineering, Vol 13, No. 5, pp 523-527.

Flow in rough steep open channels is found mostly in mountain streams and in flow overtopping protected weirs. In both cases, the energy of the flowing stream may be dissipated by artificial means so that the flowing water does not result in serious damage due to scour or erosion downstream of the main slope. One way of achieving this purpose is to lead the flow over a series of steps. (12 references)

23. El Khashab, Ahmed M., Helweg, Otto, and Alajaji, Ahmed. 1987. "Theoretical Flow Model for Drop Structures," Hydraulic Engineering, Proceedings of the 1987 National Conference on Hydraulic Engineering, Williamsburg, VA, August 3-7, 1987, ASCE, Robert M. Ragan, ed., pp 1112-1117.

A theoretical model based on the momentum equation is reviewed for a trapezoidal drop structure operating in a trapezoidal channel. Preliminary qualitative results indicate agreement between the theoretical and observed data. (4 references)

F

24. Farhoudi, J., and Smith, K. V. H. 1985. "Local Scour Profiles Downstream of Hydraulic Jump," Journal of Hydraulic Research, IAHR, Vol 23, No. 4, pp 343-358.

The development of local scour holes downstream of a hydraulic jump flow during the passage of time shows certain geometrical similarities which may be expressed by relevant parameters. The paper attempts to explain the similarity existing either in the process of scour or in the profiles that the scour holes follow downstream of hydraulic jump flow. The investigation was carried out using three geometrically similar models with geometrical scale progressing by a factor of two. (9 references)

25. Ferrell, W. R., and Barr, W. R. 1963. "Criteria and Methods for Use of Check Dams in Stabilizing Channel Banks and Beds," Proceedings of the Federal Inter-Agency Sedimentation Conference, Jackson, MS, Miscellaneous Publication No. 970, Paper No. 44, US Department of Agriculture, Agricultural Research Service, pp 376-386.

Through experience and experimentation a procedure has been developed that reduces the time required to prepare plans for a stabilization system. The construction of stabilization structures is organized on an assembly line basis. Once the structure is completed, certain repair work will be required, particularly in the area of the spillway.

Experience has shown that annual inspections are needed after each storm season to assure correction of maintenance problems.

26. Fiuzad, A. A. 1987. "Head Loss in Submerged Drop Structures," Journal of Hydraulic Engineering, ASCE, Vol 113, No. 12, pp 1559-1562.

This note describes a model study of a drop structure where, for the 100-year flood discharge, the height of drop was smaller than the depth of flow in the channel. The structure was to be used for grade control on a storm drainage channel. The purpose of the study was to find an economical stilling basin for the structure. (3 references)

27. Fletcher, B. P., and Grace, J. L., Jr. 1973. "Cellular-Block-Lined Grade Control Structure; Hydraulic Model Investigation," Miscellaneous Paper H-73-7, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

A 1:4-scale physical model study was conducted to investigate flow characteristics and develop the geometry required for a grade control structure lined with cellular blocks to accomplish a 4-ft change in grade within a trapezoidal channel conveying a discharge of 432 cfs.

28. Forsythe, Peter. 1985. "Performance of a Grade Control Structure System During Extreme Floods," 1985 Winter Meeting, American Society of Agricultural Engineers, Chicago, IL, December 17-20, 1985, Paper 85-2622, American Society of Agricultural Engineers, St. Joseph, MI.

A series of five grade control structures installed in 1980 have been subjected to three major floods since construction. The hydraulic performance of the structures and stabilization of the channel have been excellent. The straight drop structures used were found to provide flow and sediment-transport retardation. (7 references)

29. Fortson, E. P., Jr., Fenwick, G. B., Franco, J. J., and Austin, H. S. 1957. "Flood Control Project, Hoosic River, Adams, Massachusetts; Report Number 2: Model Investigation of Phase II of Improvement Works," Technical Memorandum 2-339/2, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Model investigations were conducted to verify hydraulic design of the improvement plan and to determine modifications required to provide the most economical and hydraulically sound design for high-velocity flow. A 1:20-scale model reproducing 6,800 ft of the main channel of Hoosic River and the lower 212 ft of Fiske Brook was used to check channel alignment, superelevation in bends, characteristics of weirs, stilling basin, drop structures, and treatment of intakes and outlets. Tests of the original design indicated flow conditions to be generally satisfactory. Revisions were made to improve flow conditions at the approach to a weir, at two diversion structures, and at Fiske Brook outlet. Special studies were made of minimum elevation required for all bridges. Sidewall heights necessary to prevent spillage were determined.

G

30. Gemma, Robert A., Li, Ruh-Ming, and Simons, Daryl B. 1982. "Soil-Cement Grade Control Structures," Proceedings, 1982 International Symposium on Urban Hydrology, Hydraulics and Sediment Control, Lexington, KY, July 27-29, 1982, University of Kentucky, Water Resources Research Institute, pp 125-129.

    Grade control structures are used to stabilize stream channels where general degradation and headcutting threaten the stability of existing structures or otherwise create the potential for financial loss.

    An alternative to a large reinforced concrete structure is a series of smaller grade control structures constructed of weaker, less expensive materials. Where sandy soils are present, grade control structures may be constructed of soil-cement. This approach to channel stabilization was recently taken in Pima County, Arizona, by Simons, Li and Associates, Inc. This paper presents the developed design methodology. (4 references)

31. Gill, M. A. 1979. "Hydraulics of Rectangular Vertical Drop Structures," Journal of Hydraulic Research, IAHR, Vol 17, No. 4, pp 289-302.

    Previous works of Moore, White, and Rand on the characteristics of the free overfall drop structures are briefly reviewed. A simple theory initially proposed by White is modified by introducing less drastic assumptions than the ones on which White's theory is based. The resulting theory is in closer agreement with experiment and the empirical equations of Rand than White's theory. Experimental results are also given. (9 references)

32. Goitom, T. Giorgis, and Zeller, Michael E. 1989. "Design Procedures for Soil-Cement Grade-Control Structures," Hydraulic Engineering: Proceedings of the 1989 National Conference on Hydraulic Engineering, New Orleans, LA, August 14-18, 1989, ASCE, Michael A. Ports, ed., pp 1053-1059.

    Grade control structures are effective channel stabilization measures that may be used singly or as a part of a stabilization plan. Grade control structures can range in complexity from simple rock riprap to soil-cement drop structures to large concrete structures with baffled aprons and stilling basins. This paper presents a step-by-step design procedure for soil-cement grade control structures in sand bed channels, and the application of the procedure in practice is demonstrated by using a case study of a channelization project along San Diego Creek in the City of Irvine, CA. (3 references)

33. Goon, H. J., and Brevard, J. A. 1976. "Hydraulic Design of Riprap Gradient Control Structures," Technical Release No. 59 (see complete entry under US Department of Agriculture).

34. Grace, John L., Jr., and Bhramayana, Potong. 1980. "Kaskaskia River Grade-Control Structure and Navigation Channel, Fayetteville, Illinois;

Hydraulic Model Investigation," Technical Report HL-80-20, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

The structure proposed at the head of the Kaskaskia River navigation channel near Fayetteville was designed to maintain existing water surfaces without aggravating headcutting and upstream bank erosion. A 1:25-scale model investigation was conducted to evaluate the hydraulic performance of the structure including discharge characteristics of the weir, velocities of flow through the structure and in the downstream navigation channel, general flow patterns, and riprap needed for stability of the structure and for protection of the navigation channel. The proposed grade control structure is constructed of riprap and an additional 899 ft of bank protection will be provided immediately downstream. The total structure width is 600 ft and includes a trapezoidal weir with a base width of 120 ft. The original design structure performed satisfactorily with discharges ranging from 1,000 to 35,000 cfs; however, the headwater was below desirable levels. Several modifications of the weir portion of the structure were developed to maintain existing headwaters and provide satisfactory hydraulic performance.

H

35. Hadley, R. F. 1965. "Characteristics of Sediment Deposits Above Channel Structures in Polacca Wash, Arizona," Proceedings of the Federal Inter-Agency Sedimentation Conference, Jackson, MS, Miscellaneous Publication No. 970, Paper No. 80, US Department of Agriculture, Agricultural Research Service, pp 806-810.

Deposition caused by the construction of dams on Polacca and Wepo Washes since 1945 is estimated at 7,500 acre-ft. Longitudinal profiles were surveyed above each dam on Polacca Wash. The present channel gradients on the sediment deposits vary from 0.0005 ft/ft to 0.0037 ft/ft. The gradients of these channels prior to dam construction ranged from 0.0040 ft/ft to 0.0058 ft/ft.

The conclusion is that a change in stream regimen caused by a rising base level such as a dam will reduce the channel slope and cause aggradation upstream to a higher elevation than that of the channel control. The extent of this deposition may be affected by valley width, channel slope, particle size of available material, and influence of riparian vegetation. The relative importance of each of these factors has yet to be determined. (4 references)

36. Hager, W. H., and Bretz, N. V. 1986. "Hydraulic Jumps at Positive and Negative Steps," Journal of Hydraulic Research, International Association of Hydraulic Research, Vol 24, No. 4, pp 237-253.

The hydraulic flow features associated with a hydraulic jump over positive and negative steps are investigated. Attention is paid to the length of the jump to use in the design of the stilling basin. In particular, the sequent depth ratio, the length characteristics, and the wave formation are analyzed by elementary means and confirmed by observations. A comparison of two energy dissipators is presented. (15 references)

37. Hanson, G. J., Lohnes, R. A., and Klaiber, F. W. 1986. "Gabions Used in Stream Grade-Stabilization Structures: A Case History," Hydraulics and Hydrology, Transportation Research Record 1073, Transportation Research Board, National Research Council, Washington, DC, pp 35-42.

Grade stabilization structures have been effective in controlling the degrading of streams in western Iowa. However, 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, a gabion drop structure was designed, built, and monitored for 2 years after completion. 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. (6 references)

38. Harvey, Michael D. 1984. "A Geomorphic Evaluation of a Grade-Control Structure in a Meandering Channel," River Meandering, Proceedings of the Conference Rivers '83, New Orleans, LA, October 24-26, 1983, ASCE, Charles M. Elliott, ed., pp 284-294.

The performance of a two-stage grade control structure located in Middle Fork, Tillatoba Creek, Mississippi, was evaluated 4 years after construction. The structure was designed to prevent the upstream migration of incision, and to provide flow control to rehabilitate eroded downstream reaches. Morphometric data for three channel conditions were analyzed: 1954 natural channel, 1975 preconstruction, and 1982 postconstruction. The data show that flow control significantly reduced downstream channel erosion. Channel erosion is continuing upstream of the structure. The mean upstream channel slope (0.0014) is twice the design slope (0.0007) because of channel shortening during construction and a subsequent cutoff (2,970 ft (905 m)). Backwater conditions during bank-full discharge (25-year flow) cause bank saturation and ultimately failure. Increased water-surface slope during recessional flows permits the transport of the failed bank material. Channel widening will continue until slope is reduced by channel lengthening. In the absence of channel widening, channel length will have to double for the design grade of 0.0007 to be achieved. (17 references)

39. Harvey, Michael D., and Watson, Chester C. 1988. "Channel Response to Grade-Control Structures on Muddy Creek, Mississippi," Regulated Rivers: Research and Management, Vol 2, pp 79-92.

Grade control structures are commonly employed to prevent bed degradation and concomitant bank instability of channelized reaches of rivers. A study of a 20-km reach of a coastal plains stream was conducted in 1985 to determine the effects of 12 rock-lined grade control structures that were installed between 1977 and 1983 prior to channel excavation. An allowable tractive stress method was used to determine the placement of grade control structures, and the gradients between them, for a trapezoidal-shaped channel designed to convey the 1-year recurrence interval peak flow. The design was successful in preventing bed degradation and bank erosion over the period of observation. However, unpredicted channel responses have occurred. Aggradation is apparent between control structures, and a two-stage compound channel has formed as a consequence of berm development, especially in the lower, older subreach. In the lower subreach, the vegetated berms have constricted the cross-sectional area at the design discharge (99 m^3/sec), and as a result, water-surface slope, shear stress, and unit stream power have increased. Bed material has become coarser and better sorted, which has increased shear intensity values. These unexpected changes are attributed to the lack of adequate consideration of the requirement for balance between sediment supply and transport in the allowable tractive stress method procedure. (24 references)

40. Heede, Burchard H. 1966 (reprinted 1970). "Design, Construction and Cost of Rock Check Dams," US Forest Service Research Paper RM-20, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Loose-rock, wire-bound, single-fence, and double-fence dams and one type of headcut control were designed and installed in gullies on the White River National Forest. Motorized equipment proved to be suitable for installation of the structures. Gully control was least expensive with double-fence rock check dams. Higher double-fence structures are more economical on gully gradients steeper than 5 percent. The investigations indicated that rock check dams should maintain their place in modern gully control. (7 references)

41. Hicks, Jesse L. 1974. "Chicod Creek Watershed, Pitt and Beaufort Counties, North Carolina, Environmental Statement (Revised)" (see complete citation under US Department of Agriculture).

42. Hite, John E., Jr. 1986. "Little Sioux Control Structure, Little Sioux River, Iowa; Hydraulic Model Investigation," Technical Report HL-86-5, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

The Little Sioux Project, located in Woodbury, Monona, and Harrison Counties, Iowa, consisted of remedial work on the channel of the Little Sioux River, three existing sills at the mouth of the river, and the construction of a channel control structure about 5.75 miles above the mouth. A model study of the original channel control structure was conducted to develop a satisfactory design for discharges up to 10,000 cfs. Since the construction of the original control structure, the channel has degraded 11 ft, and flows exceeding 10,000 cfs have occurred regularly. Flows exceeding the berm height scoured the side slopes causing the riprap to fail, and convergence of the concentrated flows from the right and left bank berm sections caused the development of a severe scour hole downstream of the stilling basin. High flows during the spring of 1983 caused the structure to fail so another model investigation was necessary to develop a design for the replacement structure and to determine methods to stabilize the area downstream of the structure and the channel side slopes.

Tests on a 1:25-scale hydraulic model of the replacement structure were conducted to develop the design. The model reproduced about 650 ft of topography upstream from the structure, the control structure, and 1,150 ft of topography downstream from the structure. Modifications to the original design were made to produce a structure that provided an acceptable headwater rating curve, and one with adequate energy dissipation in the stilling basin. A notched weir was developed that provided a desired range of headwater elevations for the expected discharges. The weir also produced velocities upstream and downstream from the low-flow notch for discharges less than 1,000 cfs that were considered appropriate for upstream fish migration. Stable riprap designs were determined for the channel bottom downstream from the stilling basin and the channel side slopes.

43. Hite, John W., Jr., and Pickering, Glenn A. 1982. "South Fork Tillatoba Creek Drop Structures, Mississippi; Hydraulic Model Investigation," Technical Report HL-82-22, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

The South Fork of Tillatoba Creek, Mississippi, has experienced a relatively rapid stage of channel degradation accompanied by severe streambank erosion. A two-stage, reinforced concrete grade control structure is proposed for construction by the US Department of Agriculture, Soil Conservation Service, on the South Fork of Tillatoba Creek. Tests were conducted on a 1:29-scale section model of the low-stage structure and a 1:25-scale model of the grade control structures to verify design criteria, evaluate the hydraulic performance of the structures, and make modifications to the design, where needed, to improve performance. The 1:25-scale model reproduced both the high- and low-stage control structures, approximately a 500-ft length of the upstream approach, and a 1,100-ft length of the topography downstream from the structures. Flow conditions in the approach to the low-stage structure were improved with design modifications. Energy dissipation in the low-stage structure stilling basin was improved by the addition of a trajectory curve type of drop. Approach wing walls improved flow conditions in the high- and low-stage structure stilling basins. The widths of the exit channels for both the high- and low-stage structures were reduced from their original design. Improvements were made to flow conditions in the high-stage structure exit channel by eliminating the preformed scour hole, and stable riprap designs were determined.

44. Howe, J. W. 1955. "Aeration Demand of a Weir Calculated," <u>Civil Engineering</u>, Vol 25, No. 5, p 59.

Aeration of a weir is necessary because of the entrainment of air beneath the nappe by the falling water. As the pressure is reduced, the discharge coefficient of the weir is significantly increased. Tests to determine the magnitude of the aeration demand were made using sharp-crested weirs varying in height from 2.0 to 3.5 ft, with heads up to 1.1 ft.

J

45. Jackson, B. J. 1974. "Stream Bed Stabilization in Enfield Creek, New York," New York Fish and Game Journal, Vol 21, No. 1, pp 32-46.

This study was undertaken to observe the performance of bed sills in stabilizing a high-gradient trout stream subjected to severe headcutting. Gabion structures were installed in Enfield Creek, New York, in 1967. A topographical survey of the streambed was made prior to installation and in 1968, 1970, 1971, and 1973. The sills were immediately effective in arresting headcutting and in accumulating gravel material, and they had a distinct stabilizing effect for almost 0.8 mile downstream. Gabion construction is discussed and a theory for partial failure of the two lower sills during the June 1972 flood is postulated.

K

46. Kalkanis, George. 1983. "Design and Analysis of Rock Chutes," Design Note No. 22 (see complete entry under US Department of Agriculture).

47. Kalkanis, George. 1985. "Hydraulics of Two-Stage Straight Drop Spillways" (see complete entry under US Department of Agriculture).

48. Kubo, M. M. 1983. "Placer Creek High-Velocity Channel and Debris Basin at Wallace, Idaho; Hydraulic Model Investigation," Technical Report 186-1, US Army Engineer Division, North Pacific, Hydraulic Laboratory, Bonneville, OR.

A 1:20-scale model of the Placer Creek high-velocity channel and debris basin was used to determine the adequacy of the proposed design. The model reproduced the entire 3,875-ft-long concrete-lined channel, the 420-ft-long debris basin, and approximately 620 ft of the South Fork Coeur d'Alene River at the exit of Placer Creek.

Satisfactory flow conditions in the basin were achieved when the basin was deepened and a drop structure was added at the upstream end. The model verified that the basin design was effective in trapping debris.

The original channel design proved to be satisfactory except in one area where two short reverse curves caused unacceptable waves in the channel. This condition was remedied by realigning the channel using a straight-line transition.

Movable-bed studies showed that high Placer Creek discharges would develop a large scour hole in the South Fork Coeur d'Alene River at the exit of the high-velocity channel. Although not tested in the model, a grouted riprap section was included in the prototype to minimize the scour potential.

L

49. Laursen, E. M. 1984. "Assessing the Vulnerability of Bridges to Floods," Proceedings of the Second Bridge Engineering Conference, Minneapolis, MN, Transportation Research Record 950, National Research Council, Washington, DC, Vol 2, pp 222-229.

The capacity of both new and old bridges to withstand scour at their foundations is discussed. The prediction of scour at bridge foundations is a three-step procedure: (1) the establishment of the flood magnitude-frequency relationship, (2) the conceptualization and analysis of the flow characteristics of floods that might occur during the life of the bridge, and (3) the prediction of scour. The first step needs evidence of the maximum flood that should be expected; the second step is the most difficult as a general rule; the third step is likely to raise questions about scour that have not yet been answered adequately. As a result of the Silver Bridge failure, visual examination of bridges for structural integrity has become routine. Despite occasional spectacular failures like the interstate bridge in Connecticut, there are probably more bridges lost in floods than from structural inadequacy. Recent research, sponsored by the Arizona Department of Transportation and the Federal Highway Administration, has resulted in relationships for prediction of scour at the toe of a vertical wall and at the toe of a sloping sill. The sloping sill is the preferred solution. Recent research indicates that the previous solution for sizing riprap was too conservative. Both of these studies are aids to the engineer seeking ways to make existing bridges less vulnerable. (29 references)

50. Laursen, Emmett M., and Flick, Matthew W. 1983. "Predicting Scour at Bridges: Questions not Fully Answered--Scour at Sill Structures," Report No. FHWA/AZ-83/184-3, Arizona Department of Transportation, Phoenix, AZ.

Degradation of the streambed is likely to be the reason for constructing sill structures. A discussion of the degradation phenomenon is included to serve as a guide to evaluate to what extent degradation might be a threat to a bridge, culvert, or highway. (23 references)

51. Laursen, Emmett M., Flick, Matthew W., and Ehlers, Brian E. 1986. "Local Scour at Drop Structures," Proceedings of the Fourth Federal Interagency Sedimentation Conference, Las Vegas, Nevada, March 24-27, 1986, Vol I, pp 4.60-4.69.

The scour at the toe of a vertical wall and at the toe of a sloping sill were investigated experimentally and analytically. Approximate relations for predicting the ratio of the scour depth to the (energy) critical depth were obtained for the two geometries. For the vertical wall, the sediment scoured out left in suspension, and the parameters needed to describe the scour phenomenon were the ratio of the (energy) critical velocity to the fall velocity and the drop in water surface in ratio to the critical depth. For the sloping sill, which is the

recommended geometry, the sediment scoured out left as bed load, and the parameters needed to describe the scour phenomenon were the critical depth/sediment size ratio and the ratio of the size of the riprap protecting the sill slope to the critical depth. A follow-up study of flow and scour characteristics for a vertical drop followed by an apron resulted in rules for determining the length of apron required and the range of tailwater for proper flow. (7 references)

52. Linder, W. M. 1976. "Designing for Sediment Transport," <u>Water Spectrum</u>, Vol 8, No. 1, pp 36-43.

Stream channelization is frequently employed without consideration of sediment transport characteristics of the stream, or of the extent to which the stream's natural balance will be disturbed. Erosion and sedimentation damage are the critical adverse effects. Techniques should be employed which consider sediment transport characteristics and stream equilibrium. In this way, the reactions of a stream to man-made changes can be minimized. Some of the techniques that should be considered are (1) composite channel designs, (2) extensive use of levees, and (3) grade control structures. The ultimate cost resulting from adverse effects of traditional channel modification is greater than the cost of a design that recognizes the influence of sediment transport.

53. Linder, W. M. 1963. "Stabilization of Streambeds with Sheet Piling and Rock Sills," <u>Proceedings of the Federal Inter-Agency Sedimentation Conference</u>, Jackson, MS, Miscellaneous Publication No. 970, Paper No. 55, US Department of Agriculture, Agricultural Research Service, pp 470-484.

This paper summarizes the conditions that led to the development of the channel stabilization structure for the Floyd River flood control project in Sioux City, IA, and describes the procedures followed in two model studies conducted at the University of California at Berkeley and the University of Iowa, Iowa City.

54. Little, W. C., and Daniel, Robert C. 1982. "Design and Construction of Low Drop Structures," <u>Proceedings of the Conference Applying Research to Hydraulic Practice</u>, Jackson, MS, August 17-20, 1982, ASCE, Peter E. Smith, ed., pp 21-31.

Hydraulic design criteria for low drop channel grade control structures are reviewed. Guidelines and experiences in structural design, layout, and construction are given. The hydraulic performance of a field structure is discussed. These low drop structures overcome the problems associated with low drop structures at high discharges where undulating waves are normally generated. A rock-lined stilling basin with either a baffle pier or plate is provided to dissipate the energy through the drop. (6 references)

55. Little, W. C., and Murphey, J. B. 1982. "Model Study of Low Drop Grade Control Structures," <u>Journal of the Hydraulic Division</u>, ASCE, Vol 108, No. HY10, pp 1132-1146.

Low drop grade control structures were subjected to model studies for the purpose of designing structures for installation in creeks in Mississippi and Arkansas. These structures control the severe channel degradation seen in alluvial valley streams in which headcuts or overfalls of 0.3–1.5 m in height progress upstream, causing bed scour, bank slumps and slides, and channel widening. Low drop is defined as a hydraulic drop with a relative drop height equal to or less than 1; a high drop has a value greater than 1. The relative drop height is defined as the difference in elevation between upstream and downstream channel beds divided by the critical depth. Using a model basin, tentative design criteria were developed for stilling basins for low drops with energy dissipation devices. A method is also given to determine the size and placement of a baffle pier or plate to obtain optimum flow conditions downstream. (7 references)

56. Little, W. C., and Murphey, J. B. 1981a. "Stream Channel Stability; Comprehensive Report: Project Objectives 1 thru 5; Appendix A: Evaluation of Streambank Erosion Control Demonstration Projects in the Bluff Line Streams of Northwest Mississippi," prepared for US Army Corps of Engineers, Vicksburg District, Vicksburg, MS, under Section 32 Program, Work Unit 7, USDA-ARS National Sedimentation Laboratory, Oxford, MS.

This report presents an evaluation of some of the most commonly used types of channel bed and bank revetments used on bluff line streams of the Yazoo Basin. Specific revetment techniques used on Goodwin Creek, Johnson Creek, Hotophia Creek, Tillatoba Creek, and Perry Creek watersheds were used to illustrate successes and failures. A complete section is devoted to each of these watersheds and includes the watershed description, geology, soils, and evaluation of performance of selected revetment techniques. Special attention is given in this report to a newly developed, low-cost grade control structure. During this project, 12 of these grade control structures were built and their performance was evaluated for this report. Generalized engineering design criteria for these low drop grade control structures are given in Appendix B of the general report. (55 references)

57. Little, W. C., and Murphey, J. B. 1981b. "Stream Channel Stability; Comprehensive Report: Project Objectives 1 thru 5; Appendix B: Model Study of the Low Drop Grade Control Structures," prepared for US Army Corps of Engineers, Vicksburg District, Vicksburg, MS, under Section 32 Program, Work Unit 7, USDA-ARS National Sedimentation Laboratory, Oxford, MS.

This report presents the results of hydraulic model tests for low drop grade control structures. The results are presented in dimensionless relationships. Tentative design criteria are formulated for the design of low drop grade control structures with baffle energy dissipation devices. A method is given to determine the size of the stilling basin and the size and placement of a baffle pier or baffle plate in the basin to achieve optimum flow conditions in the downstream channel. (8 references)

58. McCarley, Robert W., Ingram, John J., Brown, Bobby J., and Reese, Andrew J. 1990. "Flood-Control Channel National Inventory," Miscellaneous Paper HL-90-10, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

A US Army Corps of Engineers-wide survey of flood-control project design procedures and related experiences was conducted in 1985 to record the following: (1) specific information about various streams and promising improvement techniques, design methods used in the past, centers of experience for certain type projects, points of contact by name, and stream types existing in each Corps Division; (2) problems and noteworthy experiences pertaining to project design, environmental issues, local cooperation, Corps District operation and maintenance activities, and project review; and (3) insight into future research and guidance needs for bank protection (particularly riprap), grade control structures, and stable channel design in general.
(41 references)

59. McLaughlin Water Engineers, Ltd. 1986. "Evaluation of and Design Recommendations for Drop Structures in the Denver Metropolitan Area," report prepared for Urban Drainage and Flood Control District, Denver, CO.

This document presents an evaluation of and design guidance for drop structures in the Denver metropolitan area for the Urban Drainage and Flood Control District.

The study scope focused on analyzing drops having design flows up to 15,000 cfs, with primary emphasis on grass-lined channels having design flows up to 7,500 cfs. Flows less than 500 cfs were addressed for small drops, trickle channels, and local drainage "rundowns" for conveying minor tributary flows into major drainageways.

In the discussion, pertinent literature reviewed during the project is presented. References applicable to various topics are denoted.

Design guidance for the following basic categories is presented: (1) VRR: Vertical Riprap Drop, (2) SLR: Sloping Large Riprap Drop, (3) GSB: Grouting Sloping Boulder Drop, (4) BC: Baffle Apron (Chute) Drop, and (5) VHB: Vertical Hard Basin Drop. This report presents economic evaluations for these five drop categories, as well as the District's present sloping riprap drop design. These evaluations include both capital costs and maintenance costs. Included is an economic efficiency relationship which should be useful to designers. The efficiency relationships reflect the economy of scale and economic considerations for various drop heights and design flow rates.
(67 references)

60. Melsheimer, Edwin S., and Grace, John L., Jr. 1966. "Fremont Drop Structure and Friction Channel, Sandusky River, Ohio; Hydraulic Model

Investigation," Technical Report 2-752, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Investigations were conducted to determine the adequacy of a drop structure or a friction channel to provide flood control and fish passage facilities in a reach of the Sandusky River near Fremont, OH. The drop structure investigation was concerned with its discharge characteristics, performance of the stilling basin, the openings required for fish passage facilities, and various plans of protective stone. Modifications of the original design structure improved hydraulic performance and reduced construction costs. These modifications included lengthening the stilling basin and depressing the apron, replacing the concrete pavement downstream of the end sill with stone, providing satisfactory fish passage facilities by means of an alternate weir arrangement, reducing the width of the channel below the structure, and using a trapezoidal rather than a rectangular structure. Four types of friction channels were investigated, one of which provided the desired stages, velocities, and conditions required for fish passage.

61. Melsheimer, Edwin S., and Murphy, Thomas E. 1965. "Drop Structure, Cayuga Inlet, Cayuga Lake, New York; Hydraulic Model Investigation," Technical Report 2-709, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

The drop structure proposed for Cayuga Inlet was studied on a 1:20-scale model to determine the adequacy of the structure. Particular emphasis was placed on selection of a basin which would operate satisfactorily with tailwater depths greater than that required for a satisfactory hydraulic jump. The original design structure proved unsatisfactory, as it did not provide adequate water levels upstream from the structure; addition of a 3-ft-high crest sill was required. Use of a 12-ft-radius abutment wall instead of the wing walls of the original design reduced drawdown at the abutments, improved basin action, and reduced construction costs. Baffle piers were not required in the stilling basin, and it was found that the length of the apron could be reduced from 60 to 50 ft without a noticeable effect on energy dissipation.

62. Moore, Walter L. 1943. "Energy Loss at the Base of a Free Overfall," Transactions, American Society of Civil Engineers, Paper No. 2204, with discussion by Messrs. Merit P. White, Boris A. Bakhmeteff and N. V. Feodoroff, Carl E. Kindsvater, J. E. Christiansen, L. Standish Hall, Hunter Rouse, and Walter L. Moore, Vol 108, pp 1343-1392.

Experimental studies were made of a free overfall with a view to obtaining information that would be of value to designers of hydraulic structures. Detailed laboratory measurements showed that the energy losses at the base of a fall were of appreciable magnitude and hence must be considered in hydraulic design. These measured energy losses were applied in the development of a rational formula for calculating the height of the jump below a fall. Limited information was also obtained on the length characteristics of the jump and on the effect of submergence of the jump on energy dissipation. The presence of standing water behind the fall is explained, and its height is calculated by application of the momentum equation. (14 references)

63. Morris, B. T., and Johnson, D. C. 1943. "Hydraulic Design of Drop Structures for Gully Control," Transactions, American Society of Civil Engineers, Paper No. 2198, with discussion by John Hedberg, L. Standish Hall, J. E. Christiansen, Walter T. Wilson, N. A. Christensen and Dwight Gunder, Boris A. Bakhmeteff and Nicholas V. Feodoroff, G. H. Hickox, and B. T. Morris and D. C. Johnson, Vol 108, pp 887-940.

In the stabilization of gullies, small overflow dams are used to retain silt and to control the stream grade. These dams are simple drop structures similar to those used in irrigation canals. In this paper the development of rules for the proportioning of such dams is described in terms of the hydraulic requirements for structure performance. The formulas included in the design rules are presented graphically for convenience in application. These rules are based on the accumulated experience of engineers in irrigation and soil conservation work and on the results of a series of laboratory test programs. (15 references)

64. Murphy, Thomas E. 1971. "Control of Scour at Hydraulic Structures," Miscellaneous Paper H-71-5, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

A case is made for providing for or preforming a scour hole in which flow from a hydraulic structure can expand and dissipate its excess energy in turbulence rather than in a direct attack on the channel boundaries. Examples are given which demonstrate that riprap schemes providing for flow expansions make it feasible to stabilize the channels with rock of an economical size and provide factors of safety against riprap failure and costly maintenance.

65. Murphy, Thomas E. 1967a. "Control Structure, Little Sioux River, Iowa; Hydraulic Model Investigation," Technical Report 2-762, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

The control structure in the Little Sioux River in Monona County, Iowa, was designed to provide nonscouring velocities upstream in the channel and on the channel berms between the levees. The structure consists of a rectangular drop in the central channel flanked by rock sills on the berms. Tests on a 1:30-scale hydraulic model were concerned with capacity of the structure, effectiveness of the concrete drop, and adequacy of the rock protection for the sills, channel, and berms.

66. Murphy, Thomas E. 1967b. "Drop Structure for Gering Valley Project, Scottsbluff County, Nebraska; Hydraulic Model Investigation," Technical Report 2-760, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Tests were conducted on a 1:12-scale model of a rectangular drop structure designed to stabilize channel beds and minimize bank erosion in the Gering Valley drainage system. The majority of the tests were

conducted on a 33-ft-wide structure with a drop height of 5 ft. Discharges up to a maximum of 6,000 cfs were observed. Verification of generalized data was accomplished by tests on a structure with a 10-ft drop height. Of primary concern were development of the optimum dimensions for the various elements of the structure and determination of riprap requirements in the vicinity of the structure.

67. Myers, Chodie T., Jr. 1982. "Rock Riprap Gradient Control Structures," Proceedings of the Conference Applying Research to Hydraulic Practice, Jackson, MS, August 17-20, 1982, ASCE, Peter E. Smith, ed., pp 10-20.

The structure consists of a riprap prismatic channel with a riprap transition at each end designed to flow within the subcritical range. One design feature is that the specific energy of the flow at design discharge is constant throughout the structure and is equal to the specific energy of the flow in the channel immediately upstream and downstream from the structure. Thus, for the design discharge the dissipation of hydraulic energy in the structure is at the same rate as the energy gain due to the gradient.

The Soil Conservation Service in Mississippi has constructed 14 rock riprap gradient control structures. In Tippah County, 12 are located on Muddy Creek and 1 on Tippah River. One is located on Running Slough Ditch in Panola County. The design capacity of the structures ranges from 622 cfs (17.4 m^3/sec) to 20,600 cfs (576.8 m^3/sec). These structures have not been model tested, but they have been inspected in the field periodically. All the structures have performed as designed with regard to establishing a stable gradient in the channel in which they are constructed.

In May 1980, field surveys revealed a deep scour hole forming at the downstream end of the exit transition on the three structures farthest downstream on Muddy Creek. However, no damages have occurred to the structures themselves. Measurements of point velocity and depth at various cross sections within the prototype structure to determine velocity distribution and roughness were performed. (2 references)

N

68. Nakato, Tatsuaki. 1989. "A Review of International Literature of Design Practice and Experience with Low-Head Alluvial-Channel Grade-Control Structures," prepared by the Iowa Institute of Hydraulic Research for the US Army Engineer Waterways Experiment Station, Vicksburg, MS.

The principal objective of this investigation was to survey the international literature and to canvass the principal hydraulics design and testing organizations around the world for current information on the different types of low-head drop structures which have been developed and installed, and to review the experience with these structures. The supplemental objective was to review the applicability of existing analytical models and so-called "kinematic analysis" to small streams which are grade-controlled with single or cascaded low-head drop structures to obtain rapid yet reasonably accurate predictions of the equilibrium bed profiles of the streams. (73 references)

O

69. Oswalt, Noel R. 1978. "Model Studies of the Portugues and Bucana Rivers Channelization, Puerto Rico; Hydraulic Model Investigation," Technical Report H-78-3, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

    Two 1:30-scale physical hydraulic models of the Portugues and Bucana Rivers were used to determine the adequacy of the original designs for the flood control channelization project through the city of Ponce, Puerto Rico. The proposed channelization included trapezoidal to rectangular channel transitions, stilling basins, and drop structures in the high-velocity channels. A 3,300-ft (prototype) channel length was used to study the transitions and stilling basins including riprap stability downstream from the stilling basins. A 1,200-ft (prototype) channel length was used to study the drop structures and the adjacent riprap protection requirements. Test results indicated that the original design with certain modifications would effectively transmit all expected flood releases from the proposed Portugues and Cerrillos Dams. Modifications to transitions at entrances to the high-velocity channel reaches were streamlined within the original right-of-way to reduce surface turbulence and standing waves. Geometry of the original stilling basins was altered to prevent the oblique hydraulic jumps, and the end sill heights were lowered to reduce the water-surface drawdown, surface roller waves, and high bottom velocities downstream of each basin.

70. Oswalt, Noel R., George, John F., and Pickering, Glenn A. 1975. "Fourmile Run Local Flood-Control Project, Alexandria and Arlington County, Virginia," Technical Report H-75-19, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

    The Fourmile Run flood-control project will provide protection for the city of Alexandria and Arlington County, VA, from flooding of the Fourmile Run channel. The proposed plan for containing flood flows consists of eliminating existing constrictions in the channel; excavating and widening the channel; providing adequate bank slope protection; and constructing energy dissipators, grade control structures, and flow dividers. The investigation was conducted with a 1:30-scale model that reproduced approximately 5,700 ft of the Fourmile Run channel and 400 ft of the Long Branch tributary. The existing bridges and vertical walls, as well as the proposed improved channel with bank slope protection and hydraulic structures, were reproduced in the model. Tests encompassed flow conditions at the bridges and at the confluence of Long Branch, water-surface elevations, riprap and gabion stability, and performance of the hydraulic structures.

71. Patrick, D. M., Smith, L. M., and Whitten, C. B. 1982. "Methods for Studying Accelerated Fluvial Change," Gravel-Bed Rivers: Fluvial Processes, Engineering and Management, John Wiley & Sons, New York, pp 783-815.

To develop and manage a river basin and fluvial system effectively, it is necessary to identify and minimize the adverse effects of existing structures and activities and to predict and take into account the potential adverse effects of proposed schemes. This requires data on the factors that control the mechanics of the fluvial system. These data should cover the basin characteristics, relations between geomorphology and river mechanics, erodibility of the drainage basin, and temporal effects. In this paper some of the techniques and methods for studying accelerated fluvial change are described. Particular emphasis is placed on the importance of information on basin characteristics and on geomorphological processes to project studies.

Three case studies are used as examples of the applications of the techniques and methods described. (29 references)

72. Pickering, G. A. 1966. "Drop Structures for Walnut Creek Project, Walnut Creek, California; Hydraulic Model Investigation," Technical Report 2-730, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Walnut Creek project will provide for enlargement and rectification of the existing channels of Walnut, Lower San Ramon, and Las Trampas Creeks. Three grade control structures and one energy dissipating structure will be used to reduce velocities and dissipate excessive energy from flood flows. Model investigations were conducted on 1:20-scale models of drop structures 2 and 3. Tests were concerned with determining the optimum size and configuration of the stilling basins for these structures, the stability of the riprap downstream from the stilling basins, and the adequacy of the inlet transition upstream from drop structure 2.

73. Pickering, Glenn A. 1983. "Big Creek Flood-Control Project, Cleveland, Ohio; Hydraulic Model Investigation," Technical Report HL-83-7, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Tests were conducted on a 1:40-scale model of Big Creek to investigate the hydraulic performance of a proposed floodway channel and a section of modified channel. The model reproduced the entire proposed floodway channel, a portion of the existing Big Creek main channel, and a section of modified channel downstream from the existing channel.

The original design gabion drop structures used in the floodway to reduce the grade along the channel caused flow to concentrate near the middle of the channel, resulting in high velocities. Revisions to these drop structures resulted in good flow conditions throughout the floodway channel.

A concrete transition between the downstream end of a three-barrel conduit and the modified channel caused flow to concentrate in the channel which resulted in movement of the riprap immediately downstream from the transition and along the left bank. The concrete transition was removed, and the area was shaped with riprap. This resulted in satisfactory flow conditions in the modified channel.

74. Pima County Department of Transportation and Flood Control District. 1985. "Soil Cement Applications and Use in Pima County for Flood Control Projects," Tucson, AZ.

The primary use of soil cement in Pima County has been to reduce the erosion of unstable natural channel banks. Soil cement design specifications, engineering analysis, construction techniques, and current research are explained along with examples of the performance of soil cement bank stabilization during the October 1983 flood.

While soil cement has a long record of satisfactory service as a paving material for highways, streets, and airports, it has also been successfully used in energy and water resource projects. Applications include slope protection, seepage control, and foundation stabilization. The listed advantages of soil cement include low cost, ease of construction, and the convenient utilization of local or in-place soil, thus making soil cement applications economical, practical, and environmentally attractive.

Within Pima County, soil cement has been used for channel bank stabilization, grade control structures, channel bed protection, detention basins, landfill protection, bridge abutment protection, and as base material for highways. To date, soil cement has proven to be the only effective method of bank stabilization on the major river system in Pima County.

R

75. Rand, Walter. 1955. "Flow Geometry at Straight Drop Spillways," Proceedings, American Society of Civil Engineers, Paper No. 791, Vol 81, pp 1-13.

The flow pattern at a straight drop spillway can be described by a number of characteristic length terms: the drop length, that is, the distance from the vertical drop wall to the toe of the nonsubmerged nappe; the depth of flow at the toe of the nappe; the length of the hydraulic jump if it begins at the toe of the nappe; the depth of flow downstream from this jump; and the depth of the under-nappe pool between the drop wall and the nappe. All these values are represented in this paper as functions of the discharge and of the height of the drop. The results are given by a collective plot of dimensionless terms. Two geometrical properties of the flow pattern are established, consisting of practically constant relationships between some of the terms. The determination of flow geometry is important for the design of straight drop stilling basins. (5 references)

76. Rand, Walter. 1970. "Sill-Controlled Flow Transitions and Extent of Erosion," Journal of the Hydraulics Division, ASCE, Vol 96, No. HY4, pp 927-939.

The distance over which scour will develop downstream of a sill-controlled flow transition in an erodible open channel is determined. This determination is based on the concept of dynamic similarity and relates the erosion length in an erodible channel to the total length of flow transition in a fixed-bed channel. Accordingly, prediction of the limiting extent of erosion becomes possible for a wide variety of sill-controlled flow transitions, including the cases present in hydraulic jump stilling basins, and in a natural hydraulic jump. (6 references)

77. Rhone, T. J. 1971. "Studies to Determine the Feasibility of a Baffled Apron Drop as a Spillway Energy Dissipator, Conconully Dam Spillway, Okanogan Project, Washington," Report REC-ERC-71-29, Bureau of Reclamation, Denver, CO.

The existing spillway structure at Conconully Dam, Washington, was determined to be structurally unsafe and incapable of discharging the design flood. Installation of a conventional hydraulic jump stilling basin or flip bucket to handle the design flood was impractical because of poor foundation conditions. Preliminary investigations showed how, if the allowable unit discharge of a baffled apron drop could be increased from 60 cfs per foot of width to about 80 cfs, such a structure could be built on sound rock. Hydraulic model studies were performed to confirm a design for a baffled apron drop basin on a unit discharge of 77.7 cfs per foot of width. The tests indicated that the higher capacity structure was an effective and safe energy dissipator, and could handle unit discharges up to twice the design discharge. The effect of baffle pier location on the reservoir elevation for maximum discharge was determined. An optimum configuration for the channel bed downstream of the concrete apron was developed to prevent erosion of the apron. (1 reference)

78. Rice, Charles E., and Kadavy, Kem C. 1989. "Scour Protection at the Straight Drop Spillway," Hydraulic Engineering, Proceedings of the 1989 National Conference on Hydraulic Engineering, New Orleans, LA, August 14-18, 1989, ASCE, Michael A. Ports, ed., pp 7-12.

Tests were conducted to determine the scour and the effect of tailwater on scour downstream of the straight drop spillway stilling basin. Preliminary results are presented on performance with three riprap sizes. Spillway performance with and without wing walls is discussed. (2 references)

79. Richard, Don, Williams, Ronald K., and Swanson, Ron. 1987. "Low Head Dam Safety Studied with Hydraulic Models," Hydraulic Engineering: Proceedings of the 1987 National Conference on Hydraulic Engineering, Williamsburg, VA, August 3-7, 1987, ASCE, Robert M. Ragan, ed., pp 528-533.

Low-head dams, although very attractive to visitors, can be treacherous due to the unseen, violent, and submerged hydraulic undercurrent. Several physical models of a proposed low-head dam for Riverside Park in Grand Forks, ND, were constructed and tested. A cascade structure, although the most expensive, was recommended due to safety considerations. Video tapes of the model studies are available for public education in understanding the potential danger in the various design alternatives.

80. Robinson, Kerry M. 1989. "Overfall Stress and Pressure Distributions," Hydraulic Engineering: Proceedings of the 1989 National Conference on Hydraulic Engineering, New Orleans, LA, August 14-18, 1989, ASCE, Michael A. Ports, ed., pp 943-948.

The magnitude and distribution of hydraulic shear stress and pressure on the boundary of a straight drop overfall are presented for multiple overfall heights and flow rates. Hydraulic stress and pressure exert a major influence on headcut mechanics, as well as on conventional hydraulic structure performance. Stress and pressure were measured in time and space on the boundary of an overfall using hot-film anemometry and pressure transducers. (7 references)

81. Robles, A. 1983. "Design and Performance of Stabilizers and Drop Structures" (unpublished document).

The US Army Engineer District, Los Angeles, has made extensive use of channel stabilizers and drop structures in the design of major flood control channels in southern California. These include the Los Angeles River and the San Gabriel River Channels. This paper discusses the difference in design concept between the two and presents results of hydraulic model studies and construction techniques, as well as performance of existing structures.

S

82. Saunders, Peter A., and Grace, John L., Jr. 1981. "Channel Control Structures for Souris River, Minot, North Dakota; Hydraulic Model Investigation," Technical Report HL-81-3, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Model tests of channel control structures constructed of concrete and gabions were conducted at an undistorted scale ratio of 1:12 to determine the discharge characteristics of the structures and size and extent of riprap required to prevent scour downstream of the structures, effects of ice flowing over the structures, and stability of the gabion structures.

The gabion structure was located in a typical section of trapezoidal channel and a stable gabion configuration was developed by extending the gabions farther up the side slopes and farther downstream of the structure than was indicated in the original design.

The concrete structure was placed in an expanded section of trapezoidal channel with riprap protection on the side slopes and on the channel bottom upstream and downstream of the structure. Model results indicated that the original size and extent of protection could be reduced without endangering the structure.

Free and submerged flow discharge characteristics were determined for both types of channel control structures tested, and stability criteria were developed for the gabion structures.

83. Senoo, Katsumi, and Mizuyama, Takahisa. 1983. "Evaluation of a Sabo Dam as a Countermeasure Against Debris Flow," Proceedings, Twentieth Congress of the International Association for Hydraulic Research, Moscow, USSR, September 5-9, 1983, Seminar 2, Vol VII, Paper S.2.1, pp 280-285.

This paper describes the characteristics of two types of sabo (erosion control or check) dams to reduce sediment discharge from debris flows. Flume studies are used to examine sediment discharge behavior in silt and wall type dams. (3 references)

84. Shields, F. Douglas, Jr., and Palermo, Michael R. 1982. "Assessment of Environmental Considerations in the Design and Construction of Waterway Projects," Technical Report E-82-8, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Waterway projects covered in this report include channel modifications for flood control, navigation, dikes, streambank protection, and levees. Flood control channel modifications include clearing and snagging; channel enlargement, alignment, and relocation; and channel stabilization using grade control structures or streambank protection.

Adverse environmental impacts of flood control channel modification include loss of valuable habitats and habitat diversity, channel instability, reduction of aesthetic value, water quality degradation, and undesirable hydrologic changes.

Immediate and eventual losses of backwater habitat are a major impact of navigation channel modification projects. The major environmental impact associated with dikes is the reduction in water-surface area and loss of habitat diversity due to sediment accretion in the dike field.

Major adverse effects of streambank protection include loss of riparian vegetation and reduction in the rate of channel migration.

The major environmental impact of levees is related to their purpose: the creation of drier conditions on the landside of the levee is frequently associated with land use changes. Recent efforts to incorporate environmental considerations in levee projects include management of vegetation on and around levees for wildlife and aesthetics and recreational features. (159 references)

85. Shields, F. Douglas, Jr., Hoover, Jan Jeffrey, Nunnally, Nelson R., Killgore, K. Jack, Schaefer, Thomas E., and Waller, Terry N. 1990. "Hydraulic and Environmental Effects of Channel Stabilization, Twentymile Creek, Mississippi," Technical Report EL-90-14, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Twentymile Creek, located in northeast Mississippi, was straightened and enlarged about 1910, 1936-37, and 1966. Extreme channel instability followed the 1966 modifications, and corrective measures (placement of bank protection and construction of three grade control structures) were taken between 1982 and 1988. Hydraulic and environmental studies were performed to determine effects of the corrective measures. (83 references)

86. Shih, C. C., and Parsons, D. F. 1967. "Some Hydraulic Characteristics of Trapezoidal Drop Structures," Proceedings, Twelfth Congress of the International Association for Hydraulic Research, Fort Collins, CO, September 11-14, 1967, Colorado State University, Vol 3, pp 249-259.

This study is concerned with some of the hydraulic characteristics of flow over drop structures connecting two trapezoidal channels at different elevations. The drop structures are formed by an abrupt drop in the horizontal channel bottom, and are equipped with or without a weir. The relationships among the quantities pertinent to the hydraulic characteristics are investigated through dimensional and experimental analyses. The dimensional analysis, which was based on theoretical consideration of the flow problem, resulted in a set of dimensionless parameters, namely the relative depth, the drop number, and the geometrical parameters of the drop structure. Experimental results are presented in graphical form through dimensionless parameters for various trapezoidal drop structures. Some typical flow phenomena are shown in photographs. (9 references)

87. Smith, C. D. 1985. Hydraulic Structures, University of Saskatchewan Printing Services, Saskatoon, Canada.

Contents: Chapter I: Storage Dams (19 references); Chapter II: Spillway (26 references): Chapter III: Outlet Works (15 references); Chapter IV: Gates and Valves (11 references); Chapter V: Division Works (16 references); Chapter VI: Drop Structures (17 references); Chapter VII: Stone Structures (19 references); Chapter VIII: Conveyance and Control Structures (12 references); Chapter IX: Flow Measurement (16 references); Chapter X: Culvert Hydraulics (32 references); Appendix 1: SI Units; Appendix 2: Answers to Problems.

88. Smith, C. D., and Murray, D. G. 1975. "Cobble Lined Drop Structures," Canadian Journal of Civil Engineering, Vol 2, No. 4, pp 437-446.

This paper describes the concept and the experimental study made to determine the design criteria for a drop structure comprised entirely of loose dumped rock. The three principal components of the design were (1) the weir at the top of the slope, (2) the sloping protection downstream from the weir, and (3) the horizontal apron at the bottom.

The rock weir was intended to prevent excessive drawdown and control upstream velocities. The sloping protection was a hydraulically steep reach, on which supercritical velocity occurred. The apron was intended to accommodate the transition back to subcritical flow at the end of the drop structure.

The initial investigation involved study of the structure in two-dimensional flow. It was determined that the critical area for stability was in the terminal velocity region of the steeply sloping portion of the structure. The stone size and layer thickness required for channel stabilization were found to be a function of the channel slope and flow depth at terminal velocity. Eight combinations of variables were tested and included four different slopes, three different stone sizes, and two different layer thicknesses.

The failure process was unique in that there was an initial failure and an ultimate failure. Initial failure occurred when some stone at the lower end of the slope was displaced, exposing the subgrade. The exposed area was rapidly filled in by downstream migration of stones from further up the slope. The migration process continued until it was arrested at the top of the slope by the rock weir, and the structure became stable once again. A further large increase in discharge was required to precipitate a second or ultimate failure.

Design criteria were formulated, including a recommended factor of safety based on initial failure, and the design was verified on a three-dimensional model. (9 references)

89. Smith, C. D., and Strang, D. K. 1967. "Scour in Stone Bed," Proceedings, Twelfth Congress of the International Association for Hydraulic Research, Fort Collins, CO, September 11-14, 1967, Colorado State University, Vol 3, pp 65-73.

When stone of suitable quality and size is available near the proposed site of a hydraulic structure, the possibility of using such stone for part of the structure exists. For example, a stone-lined stilling pool may be substituted for a more costly reinforced concrete stilling basin.

Scour due to nappe impingement in a stone bed downstream from a vertical drop structure was studied. The stone size and areal extent necessary for a dependable design was determined. The data are presented in dimensionless charts.

90. Strauser, Claude N., and Denzel, Charles W. 1984. "Geomorphic Changes and Grade Stabilization of the Kaskaskia River," River Meandering, Proceedings of the Conference Rivers '83, New Orleans, LA, October 24-26, 1983, ASCE, Charles M. Elliott, ed., pp 410-417.

Design studies for the Kaskaskia River grade control structure at the head of the navigation channel on the river near the US Highway 460 bridge are described. The structure permits redredging of the upper navigation canal without upstream bank erosion and aggradation of the downstream channel bottom. Studies performed include a HEC-2 backwater model study (to obtain water-surface profiles) and a physical model study to determine discharge characteristics, water-surface elevations, etc. The proposed riprap appears adequate. (1 reference)

T

91. Taggart, William C., Pflaum, John M., Stiles, Eric A., and DeGroot, Bill. 1987. "Evaluation of and Recommendations for Drop Structures in the Denver Metropolitan Area," Hydraulic Engineering, Proceedings of the 1987 National Conference on Hydraulics Engineering, Williamsburg, VA, August 3-7, 1987, ASCE, Robert M. Ragan, ed., pp 19-24.

Numerous partial failures of drop structures constructed in the Denver metropolitan area as components of channel improvements constructed for flood control and in conjunction with urbanization, many resulting from flows less than design flows, led the Denver Urban Drainage and Flood Control District to consider a complete evaluation of drop structures. This paper discusses the first phase of the work, which culminated in a comprehensive report that was presented to the District, local government representatives, and engineering consultants at a seminar conducted in Denver on December 12, 1986.

92. Tate, C. H. 1987. "Muddy Creek Grade Control Structures, Muddy Creek, Mississippi and Tennessee," Proceedings of the Seventeenth Mississippi Water Resources Conference, Jackson, MS, March 25-27, 1987, Mississippi Water Resources Institute, Mississippi State University, Starkville, MS, pp 63-67.

Between September 1976 and September 1983, the Soil Conservation Service modified the Muddy Creek system by constructing a trapezoidal channel with 12 riprap grade control structures spaced along the main channel. Flow separation with resultant flow concentration in the exit transitions was determined to be the reason for scour downstream of the grade control structures. 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 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, 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. (2 references)

93. Turner, H. O. 1988. "Sweetwater River Channel Improvement Project, San Diego County, California; Hydraulic Model Investigation," Technical Report HL-88-3, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

In the area of proposed improvement, the Sweetwater River is a poorly defined channel varying from 1,200 to 2,000 ft wide in a relatively broad floodplain. An entrenched trapezoidal channel with a base width of 320 ft has been excavated ending just upstream of a freeway bridge. This channel has a radius of 1,000 ft and turns approximately 80 deg in relation to the proposed channel alignment through the freeway bridge. A drop structure is to be located in the radius of the curve at the beginning of the project. A study of the proposed project was conducted using a fixed bed constructed at a scale of 1:40 to study the effect of downstream waves and disturbances caused by the curvilinear flow conditions. The main objectives of the study were to obtain quantitative information on flow patterns, flow distribution, waves, and disturbances throughout the curved reach of channel, as well as to determine the effects of sediment buildup on water-surface elevations. The model study revealed that certain refinements are needed to the Sweetwater River project to eliminate potential problems.

94. Turner, Herman O., Jr., and Mulvihill, Michael E. 1987. "General Design for Modifications to Existing Lower Santa Ana Drop Structures," <u>Hydraulic Engineering, Proceedings of the 1987 National Conference on Hydraulic Engineering,</u> Williamsburg, VA, August 3-7, 1987, ASCE, Robert M. Ragan, ed., pp 1118-1123.

A model study conducted at the US Army Engineer Waterways Experiment Station investigated the possibility of utilizing the existing drop structures of the Santa Ana River to provide flood protection for the lower basin. The results of this model study show that the existing drop structures will not adequately convey the increased discharges expected without severe scour to the stream bed or structural failure. Different modifications tested included a parabolic crest, baffle blocks, and a sloping end sill. (6 references)

95. Twiss, Don. 1985. "California Rock Drop," paper presented at West States Engineering Workshop, Portland, OR, February 4-8, 1985, US Department of Agriculture, Soil Conservation Service, Davis, CA (unpublished).

California rock drops have been used as energy dissipators reducing the energy gradient to provide a stable channel.

U

96. US Army Corps of Engineers. 1970. "Hydraulic Design of Flood Control

Channels," EM 1110-2-1601, US Government Printing Office, Washington, DC.

This manual presents procedures for the design analysis and design criteria for improved channels that carry rapid and/or tranquil flows. (94 references)

97. US Army Engineer District, Buffalo. 1975. "Design Analysis: Energy Dissipator Facilities and Riprap Repair, Coy Glen and Cayuga Inlet, Ithaca, New York," Buffalo, NY.

The design analysis for this project provides: (1) two hydraulic drop structures and attached wing wall on Coy Glen; (2) soils and foundation analysis for the above structures and cantilever sheet pile wing wall alternates for the two drop structures; (3) riprap repair for the section in Cayuga Channel between the Lehigh Valley Railroad bridge and the drop structure at Station 160+00; and (4) dynamic water loads on the drop structure and hydraulic design for Coy Glenn by the Buffalo District. The design considered two types of wing walls. The factor of safety in bearing for the concrete wing walls is not considered adequate, and the more conservative steel sheet pile wing walls are recommended.

98. US Army Engineer Division, North Pacific. 1983. "Libby Reregulating Dam, Kootenai River, Montana," Technical Report 160-1, USAE Division Hydraulic Laboratory, Bonneville, OR.

The proposed Libby Reregulating Dam would be located on the Kootenai River 10 miles downstream from Libby Dam. One of the principal features of the project is combination of the spillway and powerhouse in a single structure. Design of the spillway/powerhouse was verified using three models--a 1:50-scale spillway model, a 1:35.33-scale spillway/powerhouse sectional model, and a 1:80-scale comprehensive model. Tests in both the sectional and comprehensive models were accomplished using both fixed- and movable-bed boundaries. During early stages of project design, a baffled-chute spillway was developed which provided capability for reduction in nitrogen supersaturation. Evaluation of the design accomplished in a 1:25.11-scale model is included as an appendix to this report. The spillway exhibited adequate energy dissipation for discharges up to 903 cfs per foot and potential for reduction in gas supersaturation for discharges up to 181 cfs per foot. The concept was not pursued in final design due to economics combined with operating considerations at the upstream Libby Dam.

99. US Department of Agriculture. 1975. "Bryant Swamp Watershed, Bladen County, North Carolina," Soil Conservation Service, Raleigh, NC.

Bryant Swamp Watershed, located in the southwestern part of Bladen County, North Carolina, has an area of 16,200 acres. Project measures include land treatment, 22.9 miles of stream channel modification, and six grade control structures. Environmental effects include the following: (1) reduce flooding on cropland, forested alluvial floodplain, and in the town of Bladenboro; (2) improve soil profile drainage;

(3) reduce erosion; (4) create 40 acres of wildlife food and cover; (5) provide better mosquito control; (6) create 12 jobs during construction and 8 jobs for the life of the project; (7) reduce value of 50 acres of wildlife wetland habitat; (8) damage one mile of fishing stream; (9) increase sediment during construction; (10) clear 95 acres of woodland; and (11) damage 90 acres of woodland.
(3 references)

100. US Department of Agriculture. 1973. "Burnt Creek RC&D Measure Plan for Flood Prevention, Lewis and Clark 1805 Resource Conservation and Development Project, Burleigh County, North Dakota," Soil Conservation Service, Bismarck, ND.

Works of improvement consist of a floodwater diversion, dikes, grade control structure, a structure to divert low flows to Burnt Creek, and an inverted siphon to carry irrigation water across the diversion. The project will reduce flooding on about 2,500 acres of agricultural land and a sparsely settled rural residential area; destroy 2.5 acres of woody and herbaceous cover which will be mitigated by dedicating 5 acres of similar habitat for the life of the project; provide for maintenance of the essential integrity of the existing Burnt Creek channel; provide for use of the flood diversion berm and dikes by wildlife; and provide maintenance of the floodway below the diversion (an old Missouri River channel and appurtenant dikes) in such manner as to be beneficial to project purposes and enhancement and preservation of wildlife cover.

101. US Department of Agriculture. 1974. "Chicod Creek Watershed, Pitt and Beaufort Counties, North Carolina, Environmental Statement (Revised)," Report No. USDA-SCS-WS-ES-(ADM)-72-27 (in 4 volumes), Soil Conservation Service, Raleigh, NC.

The project is concerned with Chicod Creek Watershed which is located in Pitt and Beaufort Counties, North Carolina. Project measures include land treatment, 66 miles of stream channel modification, 2 wildlife wetland preservation areas, 1 warmwater impoundment, 11 rock structures, 30 water-control structures, and 10 sediment traps. A summary of environmental impact and adverse environmental effects is given. (63 references)

102. US Department of Agriculture. 1971. "Criteria for the Hydraulic Design of Impact Basins Associated with Full Flow in Pipe Conduits," Technical Release No. 49, Soil Conservation Service, Washington, DC.

This technical release presents the recommendations on impact basins taken from the Bureau of Reclamation publication Hyd-572, "Progress Report No. XIII, Research Study on Stilling Basins, Energy Dissipators, and Associated Appurtenances; Section 14, Modification of Section 6 (Stilling Basin for Pipe or Open Channel Outlets--Basin VI)," dated June 1969, by G. L. Beichley. This release presents these recommendations as criteria for impact basins associated with the full pipe flow and pipe diameters from 1.5 to 5.5 ft, inclusive. The user may obtain the proportioning of the impact basin and the sizing of the required riprap from the included drawings.

103. US Department of Agriculture. 1983. "Design and Analysis of Rock Chutes," Design Note No. 22, Soil Conservation Service, Washington, DC.

This design note presents a simple procedure for the design of riprap chutes. The note has been developed from established data and theory regarding hydraulic resistance and rock stability to make available a technically sound method for the design of riprap chutes. The theoretical basis of the method uses a friction formula for flows along boundaries with discrete and movable roughness elements and a stability relationship prescribing the condition of incipient movement of these elements.

104. US Department of Agriculture. 1977. "Design of Open Channels," Technical Release No. 25, Soil Conservation Service, Washington, DC.

This release covers procedures for design of open channels and related measures such as floodways. Criteria and standards applicable for each situation should be used in conjunction with these procedures. Designers of open channels should find this release useful in considering the numerous technical aspects that are important to sound channel modifications. Close coordination of many technical fields is important if channels with minimum environmental impacts are to be developed.

105. US Department of Agriculture. "Drop Spillways," Engineering Handbook, Section 11, Soil Conservation Service, Washington, DC.

This handbook presents in brief and usable form information on the application of engineering principles to the problems of soil and water conservation.

The scope is necessarily limited to phases of engineering which pertain directly to the program of the Soil Conservation Service. Therefore, emphasis is given to problems involving the use, conservation, and disposal of water, and the design and use of structures most commonly used for water control. Typical problems encountered in soil and water conservation work are described, basic considerations are set forth, and all of the step-by-step procedures are outlined to enable the engineer to obtain a complete understanding of a recommended solution.

106. US Department of Agriculture. 1976. "Hydraulic Design of Riprap Gradient Control Structures," Technical Release No. 59 with Supplements 1 (1976) and 2 (1978) and Amendment 1 (1986), Soil Conservation Service, Washington, DC.

This technical release presents the criteria and procedures for the design and proportioning of riprap gradient control structures (RGCS). It is a structure consisting of a prismatic channel with a converging inlet transition at the upstream end and a diverging outlet transition at the downstream end of the prismatic channel. Its essential feature is that the specific energy of the flow at design discharge is constant throughout the structure and is equal to the specific energy of the flow in the channel immediately upstream and downstream of the structure. Thus, the dissipation of hydraulic energy in the structure is at the same rate as energy gain due to the gradient. The structure, which is made steeper and narrower than the adjoining channel upstream and downstream, maximizes energy dissipation. A computer program, written in FORTRAN, determines dimensions and parameters associated with the design of an RGCS.

107. US Department of Agriculture. "Hydraulics," Engineering Handbook, Section 5, Soil Conservation Service, Washington, DC.

This handbook presents in brief and usable form information on the application of engineering principles to the problems of soil and water conservation. Emphasis is given to problems involving the use, conservation, and disposal of water, and the design and use of structures most commonly used for water control. Typical problems encountered in soil and water conservation work are described, basic considerations are set forth, and all of the step-by-step procedures are outlined to enable the engineer to obtain a complete understanding of a recommended solution.

108. US Department of Agriculture. 1985. "Hydraulics of Two-Stage Straight Drop Spillways," Report No. PB85-174688, Soil Conservation Service, Washington, DC.

The report identifies the five flow regimes likely to occur during the passage of outflow hydrographs over two-stage straight drop spillways and presents a method for developing rating curves for such structures under any flow conditions. The advantages of the method are fully appreciated only in applications where at least one of the two stages is susceptible to submergence. The components of the compound section delineating the crest of the spillway may be rectangular or trapezoidal weirs. Satisfactory performance of the structure, in regard to energy dissipation, dictates symmetrical configuration of the compound section about the axis of the lower stage. The method can be used in the development of rating curves for existing structures not meeting the aforesaid performance requirement. (11 references)

V

109. Vanoni, V. A., and Pollak, R. E. 1959. "Experimental Design of Low Rectangular Drops for Alluvial Flood Channels," Report No. E-82, California Institute of Technology, Sedimentation Laboratory, Pasadena, CA.

This report describes research work done under contract with the Berkeley Office of the US Department of Agriculture, Soil Conservation

Service, on the use of rectangular drops as grade stabilizers in alluvial channels.

Runs were made in two flumes—one with a fixed bed and clear water, the other with an erodible bed and sediment-carrying water. Two cases were investigated in each flume: drops on mild slopes and drops on steep slopes. The dimensions of the drops were varied to establish the combinations which give the best performance.

The principal laboratory results are as follows:

1. Drops behave differently with sediment-laden flow than they do with clear flow. The sediment changes the flow pattern and enables the formation of sand waves in the channel.

2. Larger basins are required for sediment-laden flow than for clear flow.

3. The size of the scour hole downstream from a drop increases with the Froude number.

4. The dimensions of the basins for satisfactory performance increase with the Froude number.

Design curves and sample calculations are presented. The complete tabulated data are presented in the appendix. (9 references)

W

110. Water Engineering & Technology, Inc. 1988. "Performance Evaluation of Channels Stabilized with ARS-Type Low-Drop Structures," final report submitted to the US Army Engineer Waterways Experiment Station, Vicksburg, MS.

This report contains the results of an evaluation of the success of channel rehabilitation by the use of ARS-type low-drop grade control structures. The basic design for these structures was developed in a series of physical model tests which began in 1974 at the ARS Sedimentation Lab in Oxford, MS (Little and Murphey 1982, item 55). These structures have been used extensively in northern Mississippi by the US Army Engineer District, Vicksburg, and the Soil Conservation Services, US Department of Agriculture. Although the model tests provided extensive data about the structure design, evaluation of field performance and response of the channel system to the structures was beyond the scope of the developmental studies. The objectives of this investigation were to (1) compare the previous model study results with field operation, (2) determine the effect of the structures on channel aggradation and degradation, (3) determine the effect of the structures on channel bank stability, and (4) ascertain the validity of using a design discharge less than the maximum channel flood capacity. (22 references)

111. Wong, R. F., and Robles, A., Jr. 1971. "Flood-Control Facilities for Unique Flood Problems," Journal of the Waterways and Harbors Division, ASCE, Vol 97, No. WW1, pp 185-203.

The unusual climatic, hydrologic, topographic, and physiographic conditions in southern California are discussed. The unusual conditions include extreme concentration of seasonal rainfall and runoff, short-duration and high-peak storms, steep topographic gradients, and combination of physiographic and cultural characteristics. Facilities include debris basins, concrete-paved channels, leveed earth channels with and without grade control structures, and continuous single levees.

112. Woolhiser, D. A., and Lenz, A. T. 1965. "Channel Gradients Above Gully-Control Structures," Journal of the Hydraulics Division, ASCE, Vol 91, No. HY3, pp 165-187.

Regression techniques are used to determine some significant factors affecting the slope of the sediment deposition profile above gully control structures and debris dams. Analyses of field data on gully control structures in Wisconsin and debris dams in California show that the original channel slope, the width of the channel at the structure, and the height of the spillway crest above the original thalweg are statistically significant variables. (20 references)