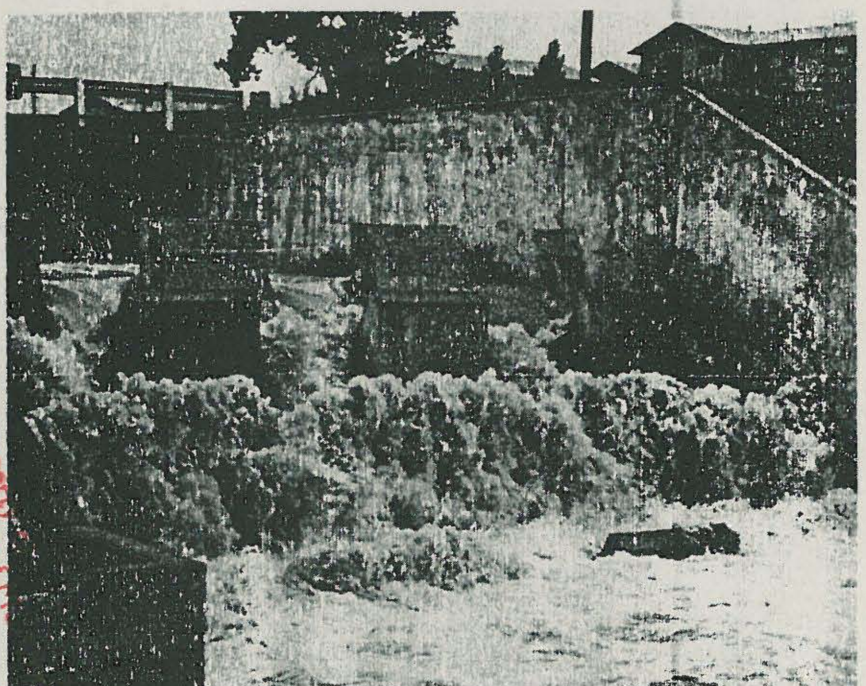
KEB

Evaluation of
and Design Recommendations for

Drop Structures in the Denver Metropolitan Area



Prepared for:
Urban Drainage and Flood Control District

McLaughlin Water Engineers, Ltd.
December 1986

URBAN DRAINAGE AND FLOOD CONTROL DISTRICT-69

L. Scott Tucker, Executive Director

2480 W. 26TH AVENUE · SUITE 156 B · DENVER, COLORADO 80211 · TELEPHONE 455-6277

December 12, 1986

TO ALL INTERESTED PARTIES:

The Urban Drainage and Flood Control District has long recognized both the importance of drop structures; and the problems of design, construction and maintenance of these facilities. In order to improve the quality of the facilities being built within the District it is our intent to issue revisions to the "Urban Storm Drainage Criteria Manual" (USDCM).

The District retained McLaughlin Water Engineers, Ltd. to assist us in the evaluation of the performance of existing drop structures, and to develop information and guidance to be used in preparing revisions to the USDCM. The attached document is the culmination of the McLaughlin effort.

We will be evaluating the contents of this document for the next six months before developing revisions to the USDCM. We would like you to do the same and give us your comments. If you have occasion to design a drop structure or review someone else's design, try to use this document to see how or if it would change that design. Let us know what you like about the procedures in the document and what you don't like. Let us know what form the USDCM revisions should take, including how detailed the criteria should be. In short, this is your opportunity to tell us what you would like to see in the USDCM regarding drop structures. We look forward to hearing from you.

Sincerely,

Scott Tucker

L. Scott Tucker
Executive Director

Note: This is a review document and does not represent official policy or criteria of the District.

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December 8, 1986

Mr. William DeGroot
Chief, Flood Plain Management
Urban Drainage and Flood Control District
2480 W. 26th Avenue, Ste. 156B
Denver, CO 80211

Re: Agreement No. 85-05.03
Evaluation of and Design Recommendations for
Drop Structures in the Denver Metropolitan Area

Dear Bill:

We have completed the above mentioned project and completed our report for the first phase of this project. We look forward to participating in the dialogue that will follow from here.

We are especially pleased about the positive attitude of the many participants. All realize that there are significant problems with many of the drops and that improvements must be made. Just to emphasize and reiterate, one of the key conditions under which this study was executed was not to criticize any design or concept, but to objectively learn about various drop concepts, factually determine the situation and develop improvements to the various drop concepts. One immediate action we recommend is an orientation away from Loose Riprap Drops toward drops like Baffle Apron Drops, Vertical Hard Basin Drops and Sloping Grouted Rock Drops.

Five basic categories of drop types were formulated based on the field and office evaluation, guidelines provided for each and economic evaluation completed. This information should be useful to engineers considering different types of drops.

Thank you for the opportunity to work on this project.

Very truly yours,

William C Taggart

William C. Taggart, P.E.

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Participants and Acknowledgements

This study was directed by Mr. Bill DeGroot, Chief, Flood Plain Management, Urban Drainage and Flood Control District. In his years at the Urban Drainage District, he has developed a comprehensive view of the structures built by the District, other governmental agencies and the development community. As a result, he had the best perspective on the types of problems that were occurring on the projects of these three groups, as well as ideas for reasonable solutions. Mr. Mark Hunter, Chief of Maintenance, was also heavily involved in all aspects of the project and was responsible for much of the basic information on maintenance costs, approaches taken to date in repairs, and projecting future maintenance costs. Mr. Ben Urbonas, Chief of Master Planning, had worked heavily on the development of the Drop Structure Criteria issued in 1982, and what had taken place since its inception, particularly in the area of construction quality control. His participation in the technical aspects of the project was greatly appreciated.

Mr. Bob Hoffmaster, Chief of Construction, was influential on the types of structures that were effective, reasonable to build and cost effective. Mr. Scott Tucker, Executive Director, was influential in the overall study direction, and provided focus on the key problems and expressing the goals of the District. Mr. Kevin Stuart, who works with Mr. DeGroot, was helpful in many ways including study direction, technical issues, and in helping us to express and communicate the concepts.

The Metropolitan Engineering Consulting Community was extremely helpful, open and professional. Each group we contacted provided information on drops, some that they expressed worked well and others that had problems. Also they provided ideas and concepts that were influential in this study. Special thanks go to Larry Muller, Steve Hogeboom, and John Hamilton of Muller Engineering, Inc; Pat Mulhern and Doug Williams of Greenhorne and O'Mara; Bill Ruzzo of WRC Engineering Inc.; Dr. Michael A. Stevens, private consultant; Doug Weber at Centennial Engineers; Tom Fuentas at Holland Corporation; and Ru Ming Li at SLA. Mr. Jim Brasch and Mr. Andrew Reese at the Corps of Engineers provided information on their design guidelines; Mr. Tom Rhone at the Bureau of Reclamation provided information on model studies for stepped spillways.

Dr. D.B. Simons, who provided services on sub-consultant arrangements, was very helpful in leading us to some key references and providing background information on work that had been done by or for various agencies in the area of riprap stability. He provided background on Agricultural Research Service and rock drops that he had designed for the Denver Water Board. Besides the Urban Drainage and Flood Control District, he was a key person when we consulted with on conceptual ideas that were being investigated.

Gene Schaefer of Jorgensen, Hendrickson and Close, Inc., was helpful on providing structural design and cost guidance.

During the field evaluation phase many trips were made with members from our staff and the Urban Drainage and Flood Control District to give further background. The District had a great deal of file information which they made available so that we could develop a fairly comprehensive file on design, analysis, construction drawings and specifications, and field inspection reports during construction. The staff members of both that worked on these efforts were:

Urban Drainage and Flood Control District

Frank Rosso - Maintenance

Dave Bennetts - Maintenance

McLaughlin Water Engineers, Ltd.

John M. Pflaum, P.E., Associate

Michael R. Galuzzi, P.E., Associate

Michael Mercer, P.E., Associate

Eric Stiles (graduate student at the time, now an employee of the firm)

John Pflaum, Mike Galuzzi and Mike Mercer are members of our firm who each individually have 10 to 14 years of experience in practical hydraulics, design and construction of drop structures. Each has high quality examples of successful projects. Mike Galuzzi did has Master's work in the area of riprap stability, which was especially helpful in the field work area. All three have worked on successful grouted rock projects. Charles Hardt, the principal in our Tulsa office, provided information on several projects and different approaches.

John Pflaum was helpful in sustaining progress on the project and guiding the overall effort. Dr. Mohammed Samad was our in-house technical advisor who critiqued the rock sizing analysis and pointed out many of the latest developments in probabilistic and stochastic analysis of rock sizing analysis. Eric Stiles started this project as a graduate student at the University of Colorado and was employed mid-term to help us complete the economic evaluation.

There are several other staff members that should be recognized: Rick Assmus, Drafting; Elaine Hatcher and Julie Weber, Technical Editing; Cozette Navarro, Word Processing and Carol Steinmeyer, Report Production.

Obviously a project like this doesn't proceed without the help of many people. I would like to thank the reviewers of this project for their efforts in the coming months.

Lastly, I would like to thank my family (Naomi, Bethany, Rebecca and Kevin) for being understanding in my absence.

Bill Taggart

EVALUATION OF AND DESIGN RECOMMENDATIONS FOR DROP STRUCTURE IN THE DENVER METROPOLITAN AREA

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SECTION I

INTRODUCTION

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. This study will likely prove applicable to similar structures in other regions. After a review period, and perhaps further research, the design related material will be summarized and published as an amendment to the Urban Storm Drainage Criteria Manual (ref. 66).

SCOPE OF WORK

The study scope focused on analyzing drops showing 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.

Numerous drop structure types have been evaluated and categorized based on similar hydraulic characteristics as follows:

1. Baffled Apron (Chute) Drops.
2. Vertical Drop with Loose Riprap Basin - This includes the District Standard (ref. 63) and several other configurations.
3. Vertical Drop with Hard Basin - This category includes a variety of materials, and configurations including the SCS drop and grouted boulders.
4. Sloping Rock Drops - This includes drops constructed according to the District Criteria (ref. 63), and other configurations such as stacked boulders.
5. Sloping Grouted Rock Drops - There are a large number of these structures, some were created by design and others were created by maintenance projects which restored Sloping Rock Drops using grout.
6. Sloping Concrete Drops and Other Similar Hard Basins - This category includes U.S. Bureau of Reclamation (USBR) III, IV, and V basins (or equivalents), Saint Anthony Falls (SAF) basin, and basins of similar shape but constructed with materials such as soil cement and roller crete.

7. Low flow check structures and related erosion control measures.

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
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 (based on the District's experience). Section XIII presents this information in a graphical form. 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.

A Design Considerations (or decision) Matrix is provided with special attention given to the following subjects:

1) Soil and Foundation Precautions
2) Structures and Foundations
3) Hydraulic Phenomena
4) Suggest Hydraulic Analysis
5) Hydraulic Analysis Difficulty
6) Design Hints
7) Flow and Drop Height Suitability
8) Construction Concerns, including: difficulty, material quality and availability, and suggested quality control measures including inspection.
9) Aesthetic Problems and Suggestions

10) Public Acceptability

Finally, the scope of work required a discussion of research needs. This includes specific guidance related to the GSB and the VHB drops which are already being implemented, but for which research would be especially useful. Other research related to rock and riprap is discussed.

ADDITIONAL INVESTIGATIONS COMPLETED

During the course of the study, four topics emerged which warranted more detailed investigations than originally conceived in the study scope. The following paragraphs highlight these four topics.

Trickle Channels

Many or most of the existing drops do not provide for a significant trickle flow conveyance through the crest. In the field, this resulted in aggradation and loss of channel conveyance upstream of the drop. The design implication of providing a contiguous trickle channel is that much higher unit discharges will occur in this area, causing a jet or a portion of the flow in the basin to remain in a supercritical flow condition and potentially force a portion of the jump further downstream. On the other hand, a portion of the vertical height of a design trickle channel could be used to create a deeper tailwater in the main portion of the basin.

Hydraulic Analysis of the Drop Profiles through the Trickle Channel and Main Drop Area

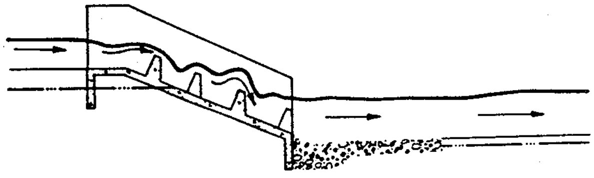
A computer program was developed to allow simultaneous hydraulic analysis of the trickle channel zone through the drop and the main portion of the drop. It provided analysis of the supercritical flow down the face of a sloping drop, and determination of the location where the jump would begin.

Rock Sizing Criteria

There is an extremely high failure incidence for sloping riprap drops. It was apparent that there were major construction problems. It was also apparent that a more conservative approach needed to be developed and evaluated against (refined by) the successes and failures in the field. A fairly extensive literature search (part of the original project scope) lead to the development of an approach that combined the work of several research projects and was tested against the Denver drop cases. This analysis method was tied to the previous computer analysis, which allowed evaluation of field cases for which data was developed, as well as 200 hypothetical cases representing the situations typically encountered.

Grouted Rock Analysis

A rational approach to the design of grouted rock was developed based on force analysis. The cases above provided information which was expanded by computer analysis to determine the force balance for trial designs. This resulted in a guideline being developed which designated minimum rock and grout thicknesses. Also, the basis of the analysis is explained so that other engineers can use or modify this approach in their work.



SECTION II
BAFFLED APRON DROPS

INTRODUCTION

The United States Bureau of Reclamation (USBR) has developed design standards for a reinforced concrete chute with baffle blocks on the sloping face of the drop. They are commonly referred to as baffle block or baffle chute drops. There are two excellent references, Hydraulic Design of Stilling Basins and Energy Dissipators (ref. 34), and Design of Small Canal Structures (ref. 1), that should be used for the design of these structures. Also, Design of Small Dams (ref. 7) presents information on Lanes Weighted Creep theory which can be used for simplified seepage analysis of these and other drops.

The design is normally recommended for a unit width flow (q) of 35 cfs/ft or less with the maximum (q) not to exceed 60 cfs/ft. In relationship to the channel width, this results in a well matched design for the UDFCD grass-lined channel criteria.

The hydraulic concept is that all of the flow repeatedly encounters obstructions that are of a nominal height equivalent to critical depth, leading to fairly complete energy loss because of the momentum loss associated with reorientation of the flow. Normally, a minimum of 4 rows of teeth are utilized to achieve disturbance of the flow and dissipation of energy. Guidelines are given for sizing and spacing the blocks. Designing for proper approach velocities is critical to structure performance.

Effectively there are fixed costs regardless of drop height for approach walls, minimum length of side walls, downstream transition walls and a minimum length of sloping apron. The baffle chute becomes more economical with increasing drop height.

This design is quite flexible in adaptation, once the hydraulic principals are understood. For instance, for low drops, designs which use two rows of baffles on the slope and two in the horizontal area below have been successful. Also, the apron can have a flatter slope than the usual 2 horizontal to 1 vertical to allow for low drops or site conditions.

Design Guidelines and Criteria for Channels and Hydraulic Structures on Sandy Soils (ref. 50) notes that these drops can be adapted to downstream bed degradation by adding more baffles on a slope extension. The USBR states that design flow limits have been exceeded at several locations with no significant problems.

Downstream of the baffled chute, the USBR recommends a rock filled area that will naturally rearrange to establish a stable bed condition and allow further stilling action. Grouted and concrete basins have also been used that allow good transitions to the downstream trickle and main channels. The structure lends itself to a variety of soils and foundation conditions.

The potential for debris flow must be reviewed. The Army Corps of Engineers (COE) generally recommends this type of drop for ephemeral streams, with some caution regarding heavy debris flow streams because the baffles can clog and fill the interstices, resulting in overflow and direct impingement of the jet on the downstream channel. Apparently, there have not been any serious problems in the Denver area, but then again, presently there are not many of these structures in place.

CASES

The Bureau has documented performance on numerous baffled apron drops (ref. 7). Almost all of the commentary relates to relatively minor problems, such as, the need for erosion protection in adjacent channels and above the chute walls where spray can occur, and debris problems.

All of the Denver cases perform satisfactorily. The following comments are relatively minor criticisms.

Case 1 - Meadowood Tributary, Aurora

Figure II-1 illustrates one of the drops in the Meadowood Drainageway, (a Tollgate Creek Tributary). The projects are located west of and parallel to Buckley Road, between Hampden and Yale. This project was based on an analysis which concluded that it was more economical to utilize multiple drops for grade control of a sand bed stream (referred to as a sediment transport channel) than to utilize a continuous liner. Further, it concluded that baffle apron drops were more economical (although marginally so) than several other types of drops including Soil Conservation Service (SCS) vertical and Type C Basins, USBR Type IV, and Trapezoidal Grouted Riprap using vertical drops. The design flow ranged from 1550 to 2010 cfs.

The stream had previously degraded to the point of endangering adjacent properties. Upon completion of the 3 phase construction project, the stream was stabilized. As illustrated in the photograph and confirmed by field inspection, several drops need further stabilization work along the banks, particularly below the drops. It is also interesting to note that the bottom row of baffles is not level with the water surface, indicating possible seepage or settling problems. Nevertheless, the structures appear stable. Note that fencing is used for safety. The overall appearance is reasonable.

Case 2 - Niver Creek at York

These drops were originally constructed in 1974 as part of a channel project that included a riprap channel lining. The design flow is on the order of 2600 cfs. The drops appear stable, but illustrates the need for trickle channel provisions. The originally constructed channel section was a riprap trapezoidal section. Because there is no trickle channel through the crest, and also because the first row of baffles sit directly on the crest, aggradation occurs at most flows. (See Figure II-2 and II-3). A naturally formed trickle channel exists in the aggraded material and is of a similar configuration to many others. The degree of aggradation would have certainly been reduced by construction of a trickle channel through the crest. Also, the photographs show very heavy, but also poorly graded riprap in the banks above the chute walls. Landscaping might have been more effective.

Case 4 - East Harvard Gulch between Logan and Downing

This baffle chute, was designed to pass a 25-year discharge of 2000 cfs and also to provide the hydraulic control for a side channel spillway which serves a flood storage pond. Figures II-4 and II-5 illustrate aesthetic landscaping and architectural treatments through the use of exposed aggregate finish and a decorative safety rail.

This project also illustrates the need for trickle channel provisions. Originally designed with a low flow/underdrain pipe, it soon became apparent that such a system had capacity and maintainability problems. Figure II-4 shows the upstream aggradation and the natural trickle channel that was created, much like Niver Creek (Case 2). The aggradation is greater as one moves upstream. A similar trickle channel was created downstream (Figure II-5), and aggradation there was even more significant. Originally, a loose riprap basin was constructed downstream per USBR guidelines. The UDFCD executed a maintenance project which included a hard-lined trickle channel and a grouted riprap basin. It directs flow back into the trickle channel, thereby helping to reduce aggradation caused by low flows spreading out in the channel bottom. One can also observe that aggradation downstream is still likely because of the wide channel which will carry flow having less velocity than most upstream channels.

Case 5 - Tulsa Small Vertical Drop

Figure II-6 shows one way of configuring a baffle chute for a smaller vertical drop. A row of baffles is constructed on the horizontal basin below the drop.

The USBR reports that some designs have successfully used less than 4 rows of baffles for low drops. It is also practical to use the same basic configuration, but a flatter slope.

CONCLUSIONS

The baffle apron drop is an excellent choice for a grass-lined channel except for situations where there are heavy debris flows. Once the hydraulic principles are clearly understood, the concepts can be applied and modified for many situations. For example, baffle aprons can be used for small drops and are especially suited to shallow tailwater and variable bed conditions.

It is important to incorporate a trickle channel into the design. This can be accomplished by locating the trickle channel between two baffles in the middle of the apron crest. An 18 to 24-inch depth is recommended. Rock placement in the stilling basin should be configured for positive drainage and to direct flows into the trickle channel downstream. When the conventional rock placement guidance by the

Bureau is adopted, some maintenance may be necessary because the rock can be rearranged to form a basin with a secondary drop that could potentially cause erosion problems. Landscaping measures work quite well and actually assist with the steep slope that usually exists along the chute walls.

Figure II-1

Meadowood drops on Tollgate Creek Tributary in Aurora, sand bed stream.

Figure II-2

Niver Creek at Steele, looking upstream, original riprap channel.

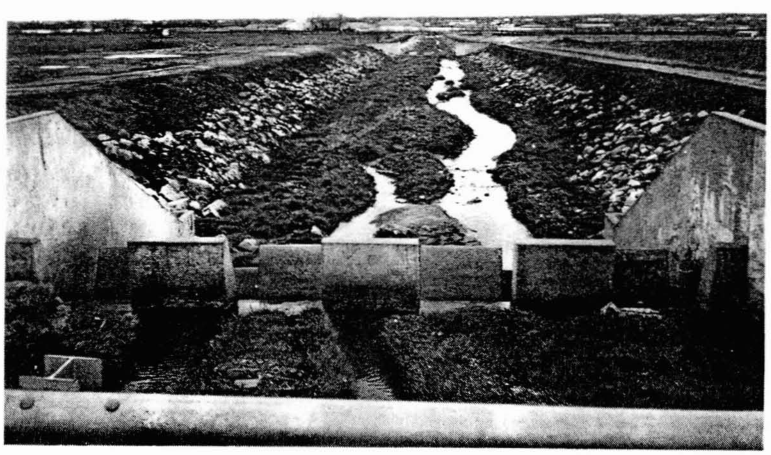


Figure II-3

Niver Creek at Steele, looking downstream. Note, aggradation and formation of a trickle/low flow channel. The trickle channel was not part of the original design.

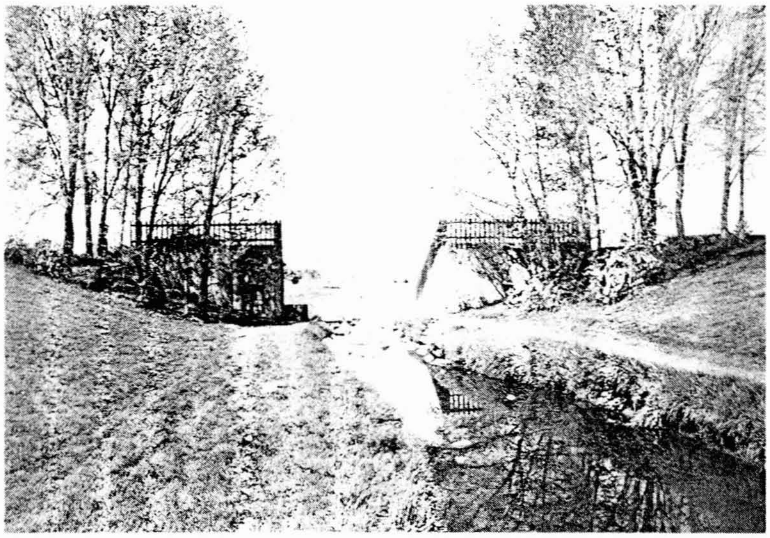


Figure II-4

Looking downstream at East Harvard Gulch drop. Note aggradation and formation of a trickle/low flow channel.

Figure II-5

Looking upstream at East Harvard Gulch. Grouted rock stilling basin helps to contain trickle flows.

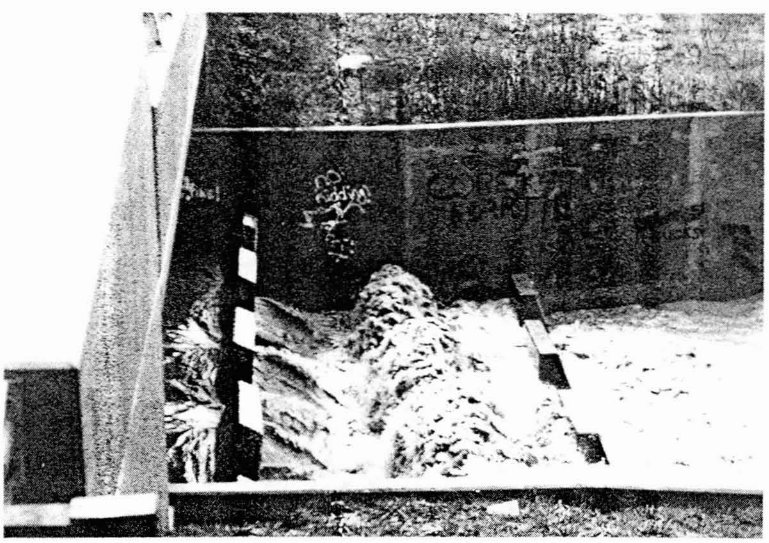
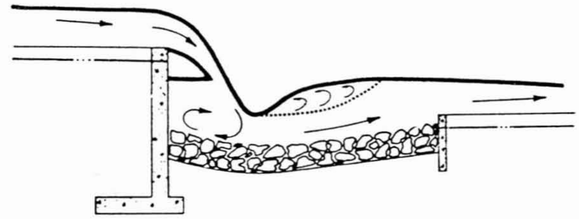


Figure II-6

Example of a small drop using a baffle apron. Baffles have been moved to the horizontal channel below. (Tulsa, Oklahoma)



SECTION III

VERTICAL DROP WITH LOOSE RIPRAP BASIN

INTRODUCTION

Energy dissipation is achieved in this type of drop by flow plunging into a pool where the energy is expended by turbulence. The pool is created by specific placement and construction of a basin, or by a "planned" rearrangement of rock by the flow.

The present UDFCD standards is described in, Design Criteria for Riprap Drop Structures (ref. 63). The criteria was based upon a presentation by Stevens, Hydraulic Design Criteria for Riprapped Chutes and Vertical Drop Structures (ref. 58) which was based upon physical model testing.

The structural design for the vertical crest wall is complicated by the lack of downstream support, seepage, soil saturation and hydraulic loading on the upstream side. In sandy or erosive soils, it is quite common to use sheet pile for crest wall construction, while caissons may prove acceptble for certain other applications. Commonly a retaining wall is used after evaluating seepage control.

CASES

There is a wide variety of crest wall alternatives for vertical drops. The following cases illustrate a number of existing applictions.

Case 29 - Little Dry Creek at Krameria, Arapahoe County

This design is referred to as a check drop and is intended to control the hydraulic grade line while leaving the invert slope at a natural or steeper gradient. The concept works best with deeper confined channels with steep side slopes, and utilizes the downstream crest to cause backwater submergence of the upstream drop. In some ways this is similar to the Corps' approach for "Derrck Stone" protection of sheet pile drops which also requires crest submergence (ref. 13, 23, see discussion in Section X).

The check structure is categorized here because the performance characteristics are considered similar to the overflow jet and plunge pool concept, illustrated by Figure III-1.

This rehabilitative maintenance project was designed for a flow rate of 500 cfs. It has experienced flows on the order of 1100 cfs. Rock was originally designed with a minimal safety factor in mind; thus, one can see the displacement of rock, the resulting scour hole, and the secondary drop downstream. The structure appears to be stable but we suspect that future maintenance will require either heavier rock to be installed utilizing UDFCD guidelines for vertical loose riprap drops, the Corps' Derrick Stone Approach, or a grouted rock basin.

We note that trickle flow scour exists downstream of the drop and aggradation occurs upstream of the drop. The observation here is that the grass-lined channels will naturally agrade or degrade to form a stable trickle channel configuration, and that trickle channels and corresponding invert elevations will rise to stay above the effective crest elevation. (Minor notches do not provide sufficient capacity to prevent aggradation). The trickle channel should be stabilized between checks.

Case 31 - Spring Creek (tributary to Little Dry Creek) downstream of County Line Road, Arapahoe County

These vertical riprap drops were originally designed to comply with UDFCD interim standards (Figure III-2). Unfortunately, the rock provided was Rhyolite which has a low specific gravity, it had to be grouted to be stabilized. Thus, it was debatable whether this drop was in a vertical riprap or vertical hard basin category. The grouting was sub-standard in our opinion, thus it was categorized here. Also, the rock is deteriorating. It is ironic that very large granite rock was used for the retaining wall which had a specific gravity of 2.7.

The basins appear stable, however, the trickle and main channels upstream show signs of aggradation. Also, the loose riprap is not well graded or placed properly and problems are likely. The design flow was 1160 cfs.

Case 33 - Sand Creek at Wheeling, Aurora

This drop is designed to handle 21,500 cfs. It appears stable as seen in Figure III-5, although there is concern regarding abutment stability when major flows overflow the ends. It may be preferable to have a deeper trickle notch as there are some signs of aggradation upstream. Rock sizing could not be verified.

Case 60 - Bear Canyon Creek Downstream of Gilpin, Boulder

This drop, depicted in Figure III-4, was originally a sloping drop with much of the rock installed on a four to one slope. Over time, the chute rock moved and a plunge pool was created. The design drawings call for a 4-foot layer of 24-inch d_{50} riprap to be provided for 30 feet downstream. We suspect that much of the material has settled in place resulting in a stable scour pool and that problems occurred during construction. It is very likely that the upstream wall influences the discharge pattern over the crest, thus increasing the intensity of scour. There are other indications of transition and riprap displacement problems downstream as noted by bank scour.

The structure was primarily designed for the 5-year event due to limited channel capacity. However, the structure was designed to be stable for the 100-year flood. Despite the visible problems, it appears that the facility is reasonably stable but will eventually require more rock work for bank and drop stability.

Case 80 - Big Dry Creek at C-470, Arapahoe County

This drop utilizes precast concrete components to form the drop and stilling basins, as shown in Figure III-5. 12-inch rock is specified for placement in the basin and 9-inch is called for downstream of the sill. It is apparent that there is excessive rock movement, secondary drops downstream of the sill, and a fair amount of channel instability that will require corrective work.

CONCLUSIONS

Vertical riprap drops appear to be a more satisfactory alternative than the present UDFCD sloping rock drops. However, there are fewer existing vertical drops than sloping drops. The likely reasons for this are expense and the engineering required for the wall. To a degree, the success of the drop is less sensitive to construction flaws than sloping riprap drops. This is because the rock will largely settle in place, which will then provide a deeper scour pool for energy dissipation (unless the scour pool jeopardizes the wall).

A trickle channel notch should be provided through the crest, and good transitions to the downstream trickle are recommended to minimize aggradation upstream and local erosion downstream. Rock movement in the basin that results in a secondary drop downstream should be avoided during construction and maintenance. The designer should make sure that the client understands and accepts the safety hazards related to the vertical drop, and the likely existence of ponded water, sediment, and debris in the riprap basin. Measures should be taken to discourage people from being near the vertical drop.

Figure III-1

Little Dry Creek at Krameria, Arapahoe, County. Check drop concept which controls hydraulic gradeline rather than channel slope.

Figure III-2

Spring Creek (Little Dry Creek Tributary), near County Line Road, Arapahoe County. Rhyolite (s.g. = 2.3) was used in channel and granite (s.g. = 2.7) for wall.

Figure III-3

Sand Creek at Wheeling, Aurora. Note potential for scour at abutments and shallow vertical depth in trickle section.

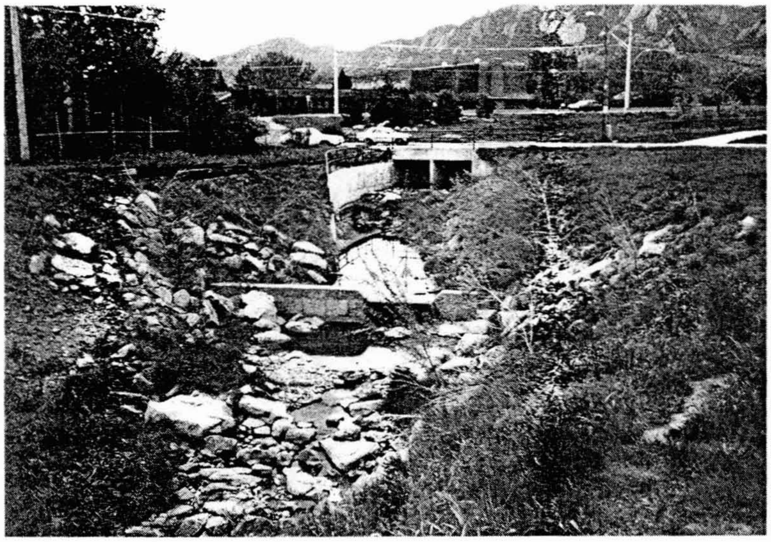


Figure III-4

Bear Canyon Creek below Gilpin, City of Boulder. This was originally a sloping drop, but the structure has evolved into a vertical drop, with riprap basin.

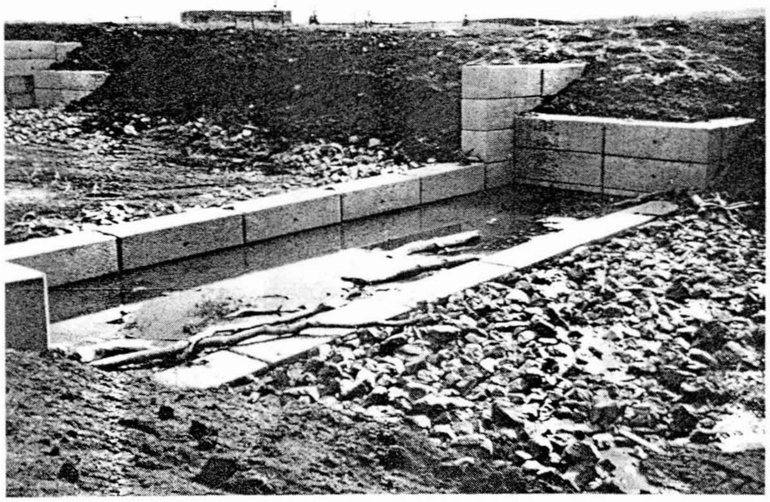
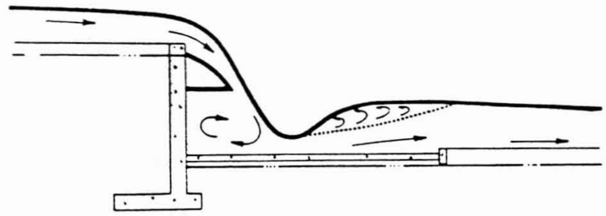


Figure III-5

Big Dry Creek at C-470, rock size too small and channel degrading.



SECTION IV
VERTICAL DROP WITH HARD BASIN

INTRODUCTION

The hydraulic phenomenon provided by this type of drop is a jet of water which overflows the crest wall into the basin below. The jet hits the hard basin and is redirected horizontally. With sufficient tailwater, a hydraulic jump is initiated. Without, the flow continues horizontally in a supercritical mode until the specific force of the tailwater is sufficient to force the jump.

CASES

A variety of components can be used for both the hard basin and the wall, various contraction effects can be implemented to reduce approach velocities, and different trickle channel options selected.

Case 26 - Goldsmith Gulch near Belleview

This is a unique design that creates a drop structure that is a focal plaza and water cascade feature in the midst of a grass-lined waterway and detention storage facility. In Figures IV-1 and 2, one can see that the basic drops are vertical, but the basins below have large blocks that also serve to dissipate energy. The design flow is 3000 cfs for the 100-year flood.

The trickle channels are very interesting because in some reaches they are actually diverted to the overbank area. The designers are continuing to perfect the facility, which is necessary of course, because there are no prototypes.

Case 27 - McIntyre Gulch, Center through West Virginia Avenue, Lakewood

Figure IV-4 illustrates improvements which included a grouted rock channel and vertical drops. The channel is steep and likely flows at a supercritical rate, thus the channel deserves monitoring. Both the walls and channel banks have subdrainage provisions. The specifications on the project called for pumped grout, vibrating into voids and cleaning the surface. Graded riprap was called for. It would have been an improvement to call for a single layer of rock for constructability, quality control (it is impossible to know if the voids are filled) and aesthetic reasons. Functionally, the project is satisfactory for a difficult location and a narrow right-of-way. This was an UDFCD maintenance project designed for 600 cfs.

Case 28 - Jack Rabbit Gulch near Simms, Lakewood

This development project utilized a SCS vertical stilling basin for a flow of 220 cfs. The basin is depressed below the channel invert and uses a row of baffle blocks in the basin which helps to shorten the basin length. A 12-inch pipe is provided for basin drainage and to provide for the trickle flows. The basins, though new, are filling with debris and there is some concern as to whether the pipe will plug. Whenever excess flows occur over the pipe capacity or there are malfunctions, the main channel soils will become saturated and lead to the eventual creation of a trickle channel (e.g. the East Harvard Gulch example - Case 4).

The safety problems are obvious. A child could easily slip under the rail (Figure IV-5), and if a person were swept into the basin with any appreciable flow depth, there would be no practical escape. It was noted that per SCS guidelines transition riprap was not provided.

Case 30 - Hidden Lake Drainageway at Clear Creek, Jefferson County

Figure IV-6 illustrates this drop, which consists of concrete and grouted rock. The trickle channel is shallow, but in this case, there is no aggradation because of the clear water release from the lake. The grouted rock upstream was added as part of the maintenance improvements due to vandalism. It was noted that more contraction and better economy could be achieved by using a much steeper slope, or even vertical ends on the crest wall.

Case 32 - Sanderson Gulch at Navajo, Denver

The drop here is similar to Cases 68.1 and 68.2 on Weir Gulch which are described in this section. (See discussion of 68.1 where concerns are expressed about the trickle channel's shallow depth, and riprap beside the concrete invert in the basin.) The riprap was grouted as part of a rehabilitative maintenance program (Figure IV-16). Though the design called for riprap downstream, aggradation has taken place to the point where the trickle channel has gained a depth of 18 to 24-inches (Figure

IV-17). Aggradation upstream of the drop has also occurred. It appears that a deeper trickle channel, and higher sill and side contractions of the vertical wall, would be helpful in providing a more stable design (in terms of not aggrading).

Case 36 - Interior Channel on Development near Lone Tree Parkway and Yosemite, Douglas County

These drops were designed to pass 450 cfs. The design is quite clean and straight-forward, but there are concerns in several areas (Figure IV-7). The timber wall will be under stress and subject to deterioration because of the wet/dry environment, particularly at the trickle channel. Also, the trickle channel is very shallow and has no provision for lateral drainage, except by allowing adjacent soils to become fully saturated. Once the area is developed, it is apparent that the basin will have minimal debris, weeds and sedimentation. The upstream rock surface is fairly well placed. The hydraulics were based on the average section, thus the jump may tend to wash downstream in the deepest section of the trickle.

Case 37 - Sanderson Gulch, Dover to Ammons, Lakewood

This is a gabion drop structure which is only of interest for its hydraulic configuration, gabions themselves have proven to be very short lived. Figure IV-8 illustrates the concept of a small vertical drop into a controlled basin. The side contraction is effective in controlling the drawdown curve upstream, and projects the nappe into the horizontal portion of the basin, rather than directing any flow onto the side slopes. However, the side slopes in the basin allow a good transition and flow dispersal downstream. The sill control is improved by widening the trickle opening and protecting the trickle channel downstream. This would also help to minimize the basin downstream. Also, providing a trickle channel through the crest would help to reduce aggradation upstream. However, this is not a major problem here because of the narrow channel and the fairly large trickle pipe through the crest. The reported capacity is 500 cfs. Overall, the configuration appears workable. Details and construction components need improvement.

Case 38 - Sanderson Gulch, 500 and 1100 feet downstream of Alameda, Denver

This drop is very similar to the previous case; however, the gabions were covered with shotcrete because of problems with vandalism. Note the visible aggradation and creation of an incised trickle channel upstream of the drop in Figure IV-9. The end of the basin has some erosion problems because of the lack of a good opening to the trickle channel and transition riprap. The basin also has siltation problems. Again, the overall configuration appears satisfactory and has potential for future use.

Case 39 - Sanderson Gulch, Arkansas to Sheridan, Denver

This case is very similar to Case 38. The reach contains many types of improvements, but the drops of concern are illustrated in Figure IV-10 and IV-11. The commentary of Case 38 applies except in the design. Concrete sill walls were added which made a better transition to the downstream channel. The sill at the trickle channel was not flush to the invert so siltation still occurred. The configuration is good except that the side walls are fairly high.

Case 42 - Goldsmith Gulch at Kenyon, Denver

This example illustrates a typical gabion failure (See Figure IV-18).

Case 56.1 - Bear Canyon Creek at Baseline, Boulder

This is a grouted stacked boulder drop (Figure IV-19), which was constructed as part of a rehabilitative maintenance project. Seepage cutoff and integrity of vertical drop are provided by concrete backfill behind stacked rocks. An alternative approach could have been taken by providing a separate cutoff treatment in the upstream trench and grouting rock to form crest. Pressure relief under the basin and adequate seepage length are important concerns in this type of design.

Case 57 - Lakewood Gulch between Meadow Creek Drive and Harlan, Lakewood

The design flow of this project is 1000 cfs, while the 100-year flood is 7600 cfs (which submerges the area completely). It consists of a simple wall with a trickle notch, and a downstream grouted rock basin (Figure IV-12). Larger rock in a single layer and holding grout lower would have improved the aesthetics. There are notes in the inspection reports regarding problems with rock sizing, placement and quality control.

Case 68.1 - Weir Gulch, South of Alameda, Denver

Figure IV-13 illustrates the drops used in this newly constructed project. They are designed for a 10-year discharge of 1700 cfs and a 100-year discharge of 2500 cfs. The basin below is a combination of concrete and loose riprap. There is concern regarding the stability of the rock, and the jump in the deepest point of the drop washing downstream. The sill downstream is small and only affects the trickle channel. It would appear that a deeper trickle channel would help by allowing deeper tailwater in the basin. Also, it appears that grouted rock would help, along with more side constriction of the crest. Like the Sanderson Gulch drops, there is merit in this concept.

Case 68.2 - Weir Gulch, Upstream of Hooker Street, Denver

The drop depicted in Figure IV-14 is the same type of drop as that in Case 68.1, constructed during an earlier phase. Some of the rock in the drop (and from upstream locations), has been displaced. Figure IV-15 is a picture of a 6-inch plastic grid overlaying the rock which was displaced. This rock has formed the secondary drop seen in Figure IV-14.

CONCLUSIONS

As can be seen in many of the previous examples, particularly Sanderson and Weir, performance of vertical drops with a hard basin has been satisfactory. However, further refinements could be made with respect to trickle channels that daylight through the crest; good drainage of the basin into the trickle channel downstream, including shaping of the sill to also provide a good transition to the overall channel; and good end contractions to keep the nappe directed into the basin.

Safety is a concern, and at a minimum, signage and fencing/railing should be provided to discourage people from getting near the drop wall. It appears that simple vertical drop walls work best, while grouted rock or concrete basins both have advantages for particular circumstances. Care with hydraulics to address general and specific conditions in the trickle channel need to be undertaken.

Figure IV-1

Goldsmith Gulch near Belleview looking upstream at one drop where trickle channel is diverted overbank.

Figure IV-2

Goldsmith Gulch near Belleview looking downstream at another drop.

Figure IV-3

Goldsmith Gulch near Belleview looking upstream at wide channel bottom.

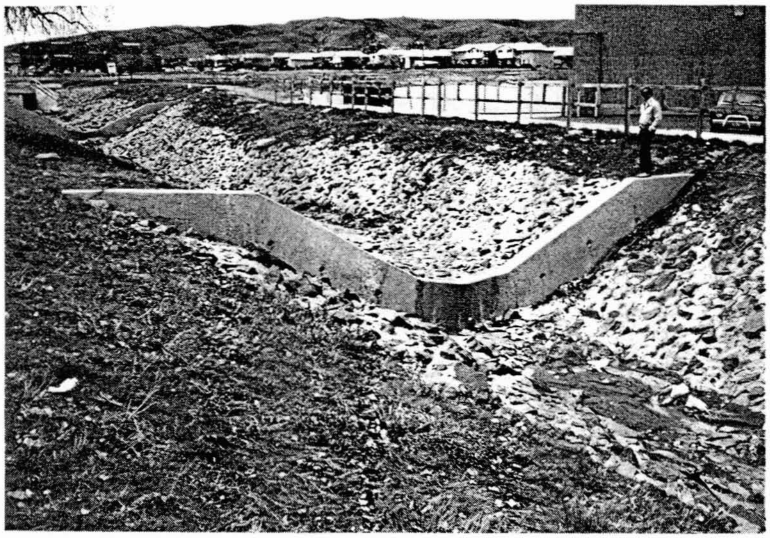


Figure IV-4

McIntyre Gulch between Center and W. Virginia Avenue. Grouted rock channel with vertical drops.

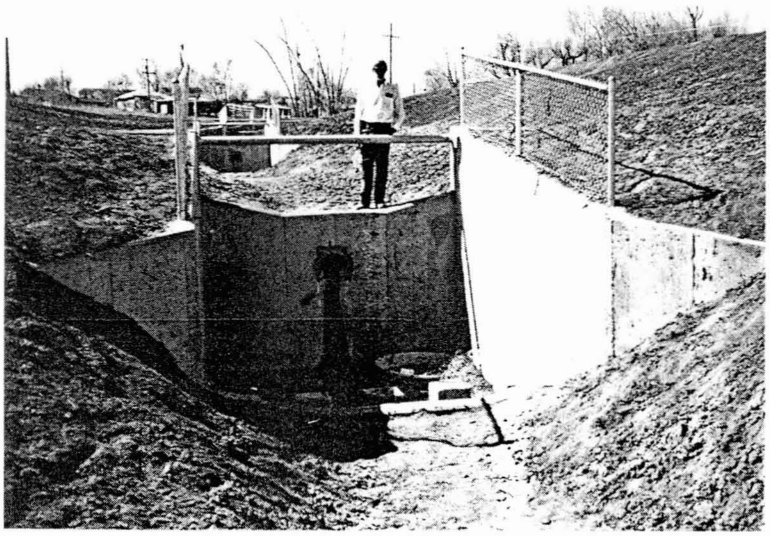


Figure IV-5

Jack Rabbit Gulch near Simms, SCS vertical basin with baffle. Pipe drains basin.

Figure IV-6

Hidden Lake Drainageway at Clear Creek. Note that rock was grouted because of vandalism.

Figure IV-7

Interior Drainage near Lone Tree Parkway and Yosemite in Douglas County. Drop using timber walls and exposed aggregate basin.

Figure IV-8

Sanderson Gulch, Dover to Ammons in Lakewood. Gabion drop with concrete sill for basin control.

Figure IV-9

Sanderson Gulch 1,100-feet downstream of Alameda, Denver, Colorado. Shotcrete added to gabion drop.

Figure IV-10

Sanderson Gulch, Arkansas to Sheridan, looking downstream at one drop. A trickle channel was added upstream. Downstream the sill wall makes transition.

Figure IV-11

Sanderson Gulch, Arkansas to Sheridan, looking upstream at another basin. There is transition from a trickle to downstream channel.

Figure IV-12

Lakewood Gulch between Meadow Creek Drive and Harlan. Grouted rock basin, and crest wall with trickle notch.

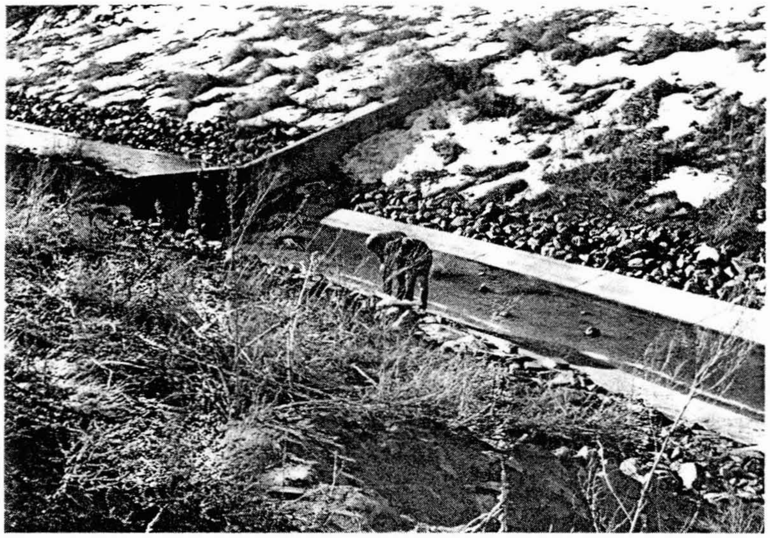


Figure IV-13

Weir Gulch above (south of) Alameda, Denver. Newly constructed drop with concrete and rock basin. Trickle has settled at crest and is quite shallow. Rock is small.

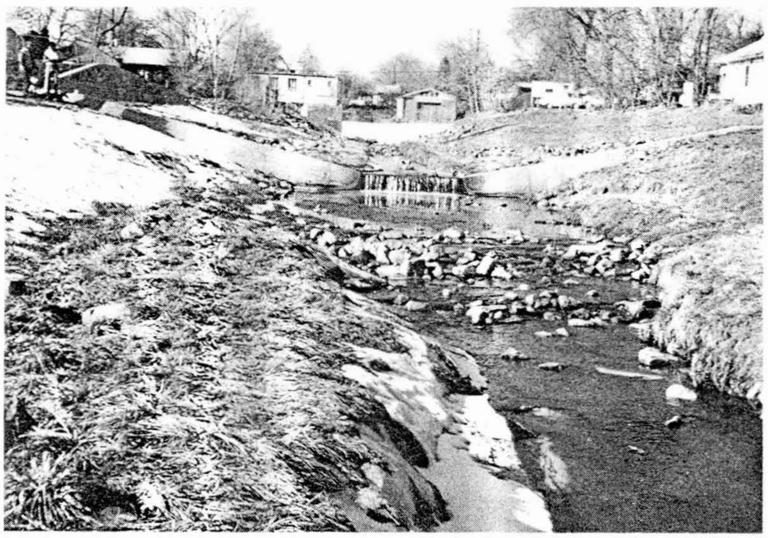


Figure IV-14

Weir Gulch above Hooker Street. Same drop as Case 68.1 (Figure IV-13), but was constructed in earlier phase. Drop is stable overall, but some rock has moved.

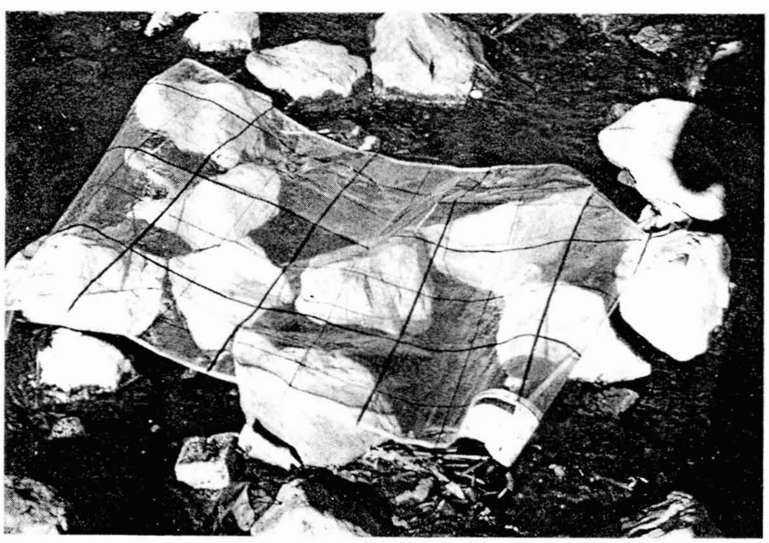


Figure IV-15

Weir Gulch above Hooker Street. Rock moved which forms secondary drop in Figure IV-14 (6-inch grid).

Figure IV-16

Sanderson Gulch at Navajo, Denver. Looking upstream at drop. Note aggradation in foreground.

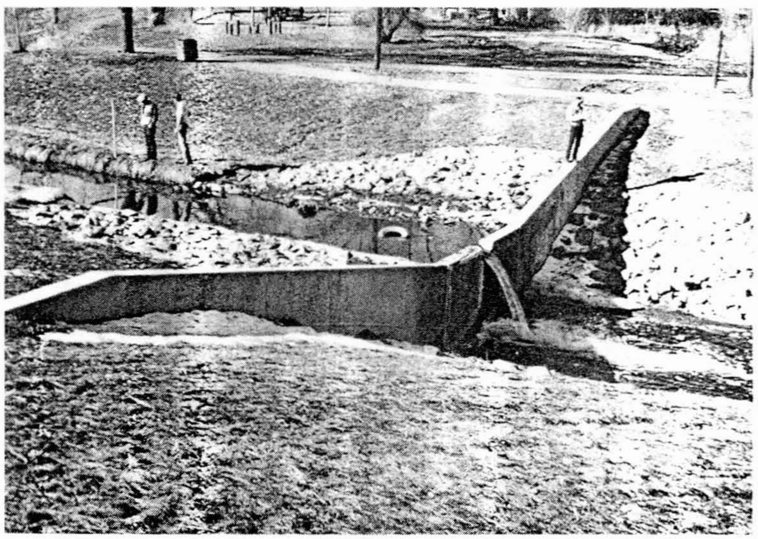


Figure IV-17

Sanderson Gulch at Navajo, Denver. Channel was originally flush to trickle channel and riprap lined. Significant aggradation has occurred and rock was grouted.

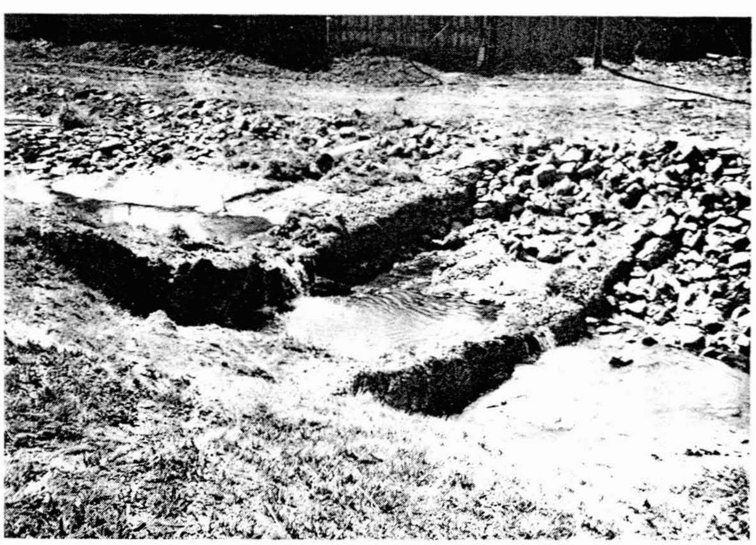


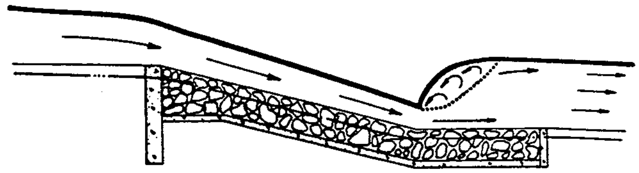
Figure IV-18

Goldsmith Gulch at Kenyon, Denver. Example of failing gabion.

Figure IV-19

Bear Canyon Creek. Grouted stacked boulders, an attractive treatment for a tight location.

SECTION V
SLOPING ROCK DROPS



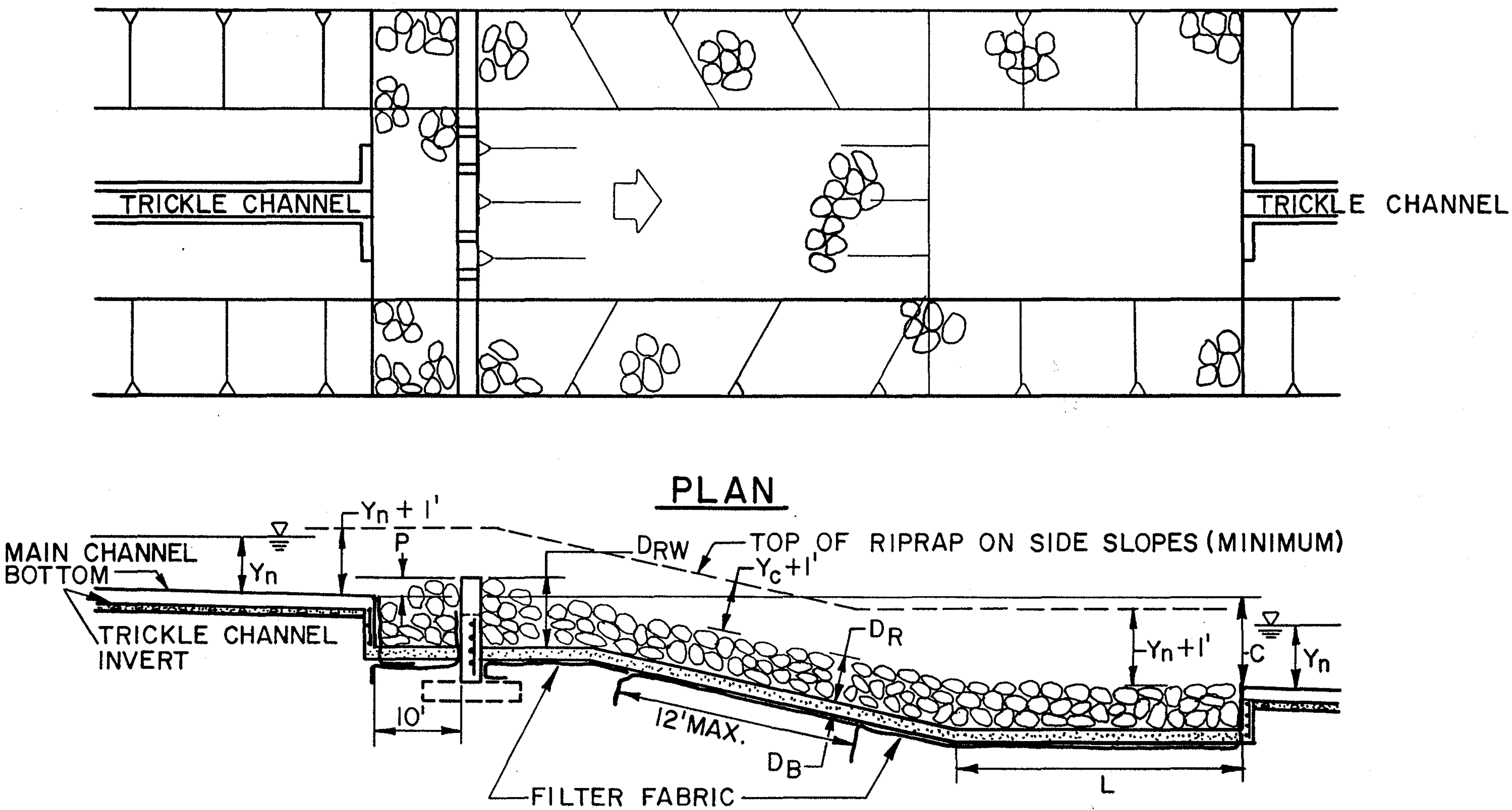
INTRODUCTION

Sloping rock drops have overall hydraulics somewhat similar to a sloping concrete drop with a conventional hydraulic jump. However, the water partially flows through the riprap which creates highly turbulent flow, and more importantly, highly fluctuating lift, shear stress and impact forces. Ongoing research at Colorado State University is occurring in this area, which indicates even higher Manning roughness coefficients than given in commonly used guidelines. This roughness, the trapezoidal shape and the flatter slopes utilized lead to a wavy undular jump where little energy is dissipated and turbulence persists downstream.

The Urban Drainage and Flood Control District distributed a guideline layout (ref. 63) for a loose riprap drop which is presented in Figure V-1. A crest wall was intended to distribute flow evenly across the drop to avoid concentrations of flow which might require heavier riprap, and to provide some seepage control. As clearly explained in the guidelines, the rock sizing was based upon the assumption of no safety factor. Rock sizing was based on the results of physical modeling which was done during the course of a drop study in Canada (ref. 52), developed for application by Stevens (ref. 58), and further confirmed by reasonable checks with other shear stress and drag/lift approaches (ref. 63). In the Canadian paper, it is very clear that at the no safety factor point, rock smaller than the d_{50} will move and the overall drop will begin rearranging into more of a stepped profile. Also, deposited rock downstream will create secondary bank scour downstream. Analytical details will be discussed in Section X.

CASES

Many of the following examples utilize the suggested District maximum guidelines, but other approaches are reviewed.



℄ PROFILE

FIGURE V-I SLOPING RIPRAP DROP STRUCTURE

NOT TO SCALE ACCORDING TO 1982 U.D.& F.C.D. GUIDELINES (REF. 63)

Case 6 - Ralston Creek at 58th Avenue, Arvada

This is what is referred to as a stacked boulder approach (see Figure V-2) designed for a maintenance project. Originally, grout was to be placed in the voids, but timing conflicts with a 404 Permit negated its use. Fortunately, the box culvert provides the seepage control. Low flows enter the voids, leaving the debris. A good depression is provided, and thus, a stable jump.

Stacked boulders drops have the upstream boulder locked behind and lower than the top of the downstream boulder. Graded riprap is used for bedding and chinking of voids. Great care was taken to level the tops to create the ledge appearance which is attractive. In a grass-lined open channel, seepage cutoff and control of erosion by piping through the voids would be essential. This is approximately a 5 foot drop.

Case 11 - Massey Draw at Carr, Jefferson County

This project was one of the earlier ones in which the designer partially used the UDFCD guidelines. The design flow is approximately 2085 cfs. The drop height is approximately 6 feet and it utilizes a 4 to 1 slope. With no stilling basin, the drop and downstream area will be stressed during major floods. As seen in Figure V-3, the drops were originally covered with soil. The rock is generally smaller than specified (d_{50} of 18-inch rather than 24-inch) and poorly graded so that voids are open to the subgrade with resulting removal of subgrade material and settling. At some drops, rock has moved downstream. Cutoff walls are not satisfactorily controlling piping. We suspect difficult backfill conditions because the wall may not have had a footer, and it is not apparent how the ends were treated. Eventually, the drops will need significant repairs.

Case 12B - Tributary L, Niver Creek, Thornton

This drop was offered only as another larger drop that failed during a heavy flood and required subsequent repair, which still is not entirely satisfactory (Figure V-4). Ultimately, it is likely that supplementary rock will be necessary as well as grouting.

Case 13 - Cherry Creek near Holly, Denver

Figures V-5 and V-6 illustrate one of the drops rehabilitated. The design called for a d_{50} of 24-inch. Figure V-5 was taken during a sustained release from Cherry

Creek Reservoir of approximately 400 cfs. Figure V-6 was taken later and indicates some rock movement. It visibly portrays that the d_{50} is on the order of 12 to 14-inches, which was physically sampled and measured by Dr. Stevens. Clearly, the lesson here is on the significant difficulty in providing, installing and inspecting riprap.

Case 14 - Little Dry Creek and Liberty Hill Tributary, Arapahoe County

Figures V-7 and V-8 illustrate the problems with the drops on the Liberty Hill tributary. Little Dry Creek actually had less significant problems, apparently because of the tailwater. Figure V-6 illustrates that the jump has a tendency to wash downstream and erode (which was verified by calculations). Note that the riprap is poorly graded and varies in size depending on location. The jet in the center has washed out the riprap (Figure V-8). Note the segregation of the rock in the picture. Very small rock is by itself on the left side of the drop, while larger, more poorly placed rock is on the right. The d_{50} of the rock was supposed to be 2 feet, clearly the rock is inadequate and thus the displacement. The flow range for the Liberty Hill tributary is 400 cfs while Little Dry Creek is 660 cfs.

Note that the rock displacement is largely in the center of the drop and that the side slopes do not have nearly the level of damage. The design slope was 4.5 to 1, with a 20 foot basin downstream. There was no visible slope break or basin distinction, which leads to the conclusion that there is even more tendency for the jump to wash downstream with the resultant erosion. Formation of a depressed basin is highly advisable to encourage jump stability, and to prevent secondary drops and erosion. Another observation is that this type of trickle channel provides for poor lateral drainage of adjacent soils. Thus, when the jump washes downstream during a flood, the soils adjacent to the trickle are especially vulnerable because vegetation will be poorly established and the soils are inherently weak.

Case 15 - Lone Tree Creek near South Tucson Way, Arapahoe Airport Center, Arapahoe County

These are a series of loose riprap drops (Figure V-9), constructed during the initiation of the present UDFCD District guidelines (ref. 63). The design flow was 1300 cfs, and there are both 2 and 3 foot drops. The slopes vary, apparently from 9 to 15%. The d_{50} that was to have been provided was 1.5 foot, but 1.0 to 1.25 was observed.

The trickle channel does daylight through the crest and has a depth of 1.3 feet. Some rock movement was noted in the trickle channel area and erosion had occurred downstream of the basin. Overall, the appearance is good and the drop appears to be stable. The flatter slopes appear to be a positive factor. Some movement of rock immediately upstream of the crest is observed, but further upstream there appears to be some minor aggradation.

The concept of the trickle channel going through the crest appears workable if care is taken on rock sizing.

Case 16 - Little Dry Creek Upstream of Sheridan, Westminster

Figure V-10 illustrates one of the drops. The d_{50} specified was 18-inches, but it appears that there is a large percentage that are as large as 24-inches. These pieces lead to poorly graded riprap, and also, the rock is poorly placed with numerous pieces protruding objectionably above the design grade. A high water mark was observed, nearly as high as the upper side slopes of the drop. Many pieces of riprap had been displaced below the trickle channel area even though the trickle did not daylight through the crest. There are signs of aggradation upstream. Downstream, displaced rock forms a secondary drop and scour at the interface with the downstream channel. The drop slope is 18.7%, with no depression in the basin downstream.

Case 17 - Bear Canyon Creek between Martin Drive and Broadway, Boulder

This project is a series of 12 drops, originally constructed using gabions, which were replaced because they failed. Most of the drops were replaced with sloping riprap drops constructed with grouted rock cutoff/control crests. The Urban Drainage District contracted for and purchased the riprap. The specification called for visual inspection and assistance with sorting and measuring at the quarry. Though trips were made to the quarry, no specific gradation tests were completed. There were problems at the site with sizing and placing of the rock with a separate construction contractor, and problems with grouting the crest.

Dr. Stevens made an independent evaluation (ref. 59) of the project for the Urban Drainage District including its performance and suggested repair modification. His measurements revealed a d_{50} at most of the structures of 1.25 feet, whereas 1.5

was specified. A significant flow of water (2.5 to 4 foot depth depending on location) did occur which resulted in damage to the project at the drops, with the exception of one. Drop 5 is depicted in Figures V-11 and V-12 for post construction and post flood condition and shows only minor movement; d_{50} was 1.5. Figures V-13 and V-14 illustrate Drop 9 for the same comparison. The d_{50} of Drop 9 was reported as 1.25, but inspection of V-13 shows a lot of variation and many locations with concentrations of smaller rock. Drop 9 was so greatly changed that it is probably inappropriate to continue to regard it as a sloping drop.

A hydraulic and rock sizing analysis, performed as part of this investigation and described later in this report, found that Drop 5 was wider and thus subject to less shear stress than Drop 9. Drop 9 had smaller rock and was subject to greater hydraulic forces, thus the resultant difference in stability.

At the time of our inspection, seepage under the grouted crests was noted. This most likely correlates to construction problems with the grout cutoff, its close proximity to the thick layer of sloping rock (which decreases the cutoff effectiveness) and the porous nature of the adjacent bed materials.

We noted that although widths varied (and thus the unit discharge), the design rock size apparently did not. Also, the design drop slope was 4 horizontal to 1 vertical. The design frequency was 5 years and the design flow was 600 cfs.

Frankly, the situation is discouraging because care had been taken in rock acquisition and placement, certainly more care than had been taken in similar projects of that date.

Case 19 - Lilley Gulch East of Simms, South of Bowles (Dutch Creek Tributary), Jefferson County

There was little information available on these drops. However, the condition is satisfactory as seen in Figure V-15. Note that the trickle channel does daylight through the crest wall, and transitions out downstream. The drops are small (2 to 3 feet) and have mild slopes.

Case 20 - Tributary to Englewood Dam above East Dry Creek Road, Arapahoe County

Figures V-16, V-17 and V-18 illustrate failures for a 965 cfs design at different locations. Figure V-16 illustrates complete displacement to subgrade, while Figure V-17 illustrates the displacement of the riprap downstream. This situation will continue to worsen. The concrete cutoff walls clearly help slow the degradation process. Slopes of 5 to 1 and 8 to 1 were used, both with a design d_{50} of 18-inches. Figure V-18 shows a 6-inch mylar grid on top of the riprap, which is clearly smaller than specified.

Case 52 - South Platte River near Oxford, Englewood

This structure, designed by the Corps of Engineers (ref. 13), is designed based on modeling results (ref. 23) for a special system to protect sheet pile. The jump is submerged on the face, in fact, the design requires tailwater higher than the crest. Figure V-19 looks upstream. The rock detailing is interesting in that it utilizes a single layer of larger rock (Derrick Stone) which has a minimum dimension (38-inch), laid over graded riprap (15-inch d_{50}) which is placed on bedding and subgrade as illustrated in Figure V-20. Design flow is 16,400 cfs, slope is 10 to 1, and flow depth upstream is 11.51 ft. This installation technique has merit, even for drops with a conventional jump downstream.

Case 81 - Phillips Drainageway, Tributary to Lilly Gulch, near Yosemite and County Line Road

This case, shown in Figure V-21, depicts a failure in progress, worsening as in Figure V-22, until piping and end cutting around the cutoff wall occurrs.

CONCLUSIONS

There are very significant problems with sloping graded rock drops. There are so many failures that other options should be used as a standard practice and graded riprap should be used only in special cases (and then only with extensive engineering and field quality control).

The quality control efforts to date of the previous cases (except one), consist of "eyeball" measurements of stockpiles and placed riprap. Apparently, only the Corps of Engineers enforces specifications which require an actual gradation test of a large sample of riprap. Following their example, we recently conducted such a test. A 21 ton sample was taken from rock loaded for delivery. All larger rock was measured and sorted into small groups of similar sizes, and then weighed (Figure V-23 and V-24). Smaller sizes were segregated and weighed. Plots of the results are given in Figure V-27, both in terms of equivalent sphere diameter based on weight and measured size in terms of passing an equivalent grid, which are similar. Clearly, we found the rock to be short on larger sizes, though the group felt at the time that the gradation was reasonable using the eyeball method. Once stockpiled at the construction site, photographs of the 6-inch mylar grid varied greatly (Figures V-25 and V-26). The quarry had suggested keeping this as a visual comparative standard, but clearly one would not be able to compare with such a variation in the pile. Thus, it appears that periodic tests need to be completed.

One point worth discussing is the processing of larger graded riprap. The quarries drill and shoot according to the general sizes being demanded. The material can be sorted by rolling downhill to various benches (the largest going to the bottom) and by the loader operator mixing out of stockpile by eyeballing. Obviously, because of expense, few gradation tests are run. The process is very sensitive to the operator, and any change in personnel can result in a size change.

Another problem is handling and placement of riprap at the site. Every step results in segregation, and it is very easy to end up puting all large rock in one area (because it may be in the outside of the pile) and all smaller rock in another.

Improvements can be made if the placement approach is oriented to place all rock greater than d_{50} on the surface (on the basis that all smaller material will be worked downstream unless it is trapped by the larger fraction). Photographic standards of such rock placement (through mylar overlay grids) may allow measurable standards to allow continuous size checking. Of course, this would be in conjunction with gradation tests.

The entire subject of rock placement techniques is controversial, with different approaches being taken. Simons reports success using a well graded riprap mixture that includes sizes down to the equivalent of bedding material, and using a single layer for bank riprap. Some adjustment and follow up repairs are anticipated in this approach, and stable bank riprap is achieved.

Many of the quality tests are infrequently run, and the practice is to use very aged tests. Fractures and other discontinuities are very difficult to test for and would require inspection of the quarry and the rock.

Most of the drops have severe problems within the base width of the drop, while the riprap on the side slopes is more stable. Trickle channels that daylight through the crest do not appear to create major problems. Without trickle channels through the crest, aggradation upstream and lost flood capacity results. However, separate hydraulic analysis and rock sizing would be required when providing a trickle section thru the drop. The flatter slope drops (e.g. 10:1) appear to be more successful.

Cutoff walls appear to be a major mitigation factor where failures are occurring. In clayey soils, we percieve that more effective cutoff could be achieved by trenching in the soil and backfilling with concrete; only forming above rock subgrade.

Stacked boulders and Derrick Stone type approaches have merit. Seepage cutoff and control of erosion needs careful consideration. The hydraulics and forces on the stacked boulders have not been studied, and no real guidelines are available, thus work is needed.

Figure V-2

Ralston Creek at 58th Avenue, Arvada, stacked boulder example.

Figure V-3

Massey Draw at Carr, Jefferson County. Note poor rock gradation, undersized voids and settling of rock. Seepage noted.

Figure V-4

Tributary L. Niver Creek, Thornton, looking upstream at rock drop that failed in "Thornton Tornado". Larger rock placed afterwards.

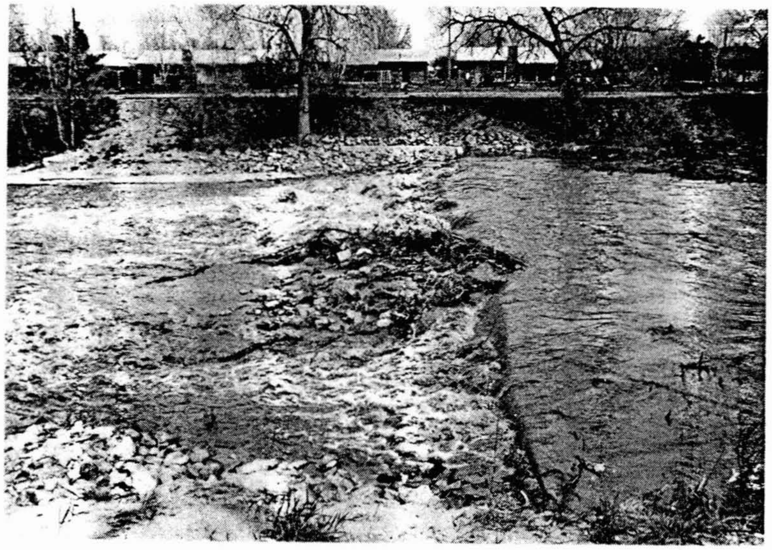


Figure V-5

Cherry Creek near Holly. Flow is approximately 400 cfs.

Figure V-6

Cherry Creek near Holly. Taken subsequent to V-6, with some movement of rock indicated and small size (12-14 d_{50}) provided rather than the 24-inch d_{50} which was specified.

Figure V-7

Liberty Hill Tributary, Little Dry Creek, Arapahoe County. Illustrates jump that washes downstream and rock movement.

Figure V-8

Liberty Hill Tributary, Little Dry Creek, Arapahoe County. Much of the rock invert is washed away.

Figure V-9

Lonetree Creek near Airport Center, Arapahoe County. 1300 cfs drop with trickle channel. Mild slope and fairly stable drop.

Figure V-10

Little Dry Creek above Sheridan Blvd., Westminster. Poorly placed and graded riprap, many larger pieces than specified d_{50} have moved, especially near the trickle channel.

Figure V-11

Bear Canyon Creek below Martin Drive, Boulder. Drop 5 immediately after construction.

Figure V-12

Bear Canyon Creek below Martin Drive, Boulder. Drop 5 after flood event stable except for minor movement.

Figure V-13

Bear Canyon Creek below Martin Drive, Boulder. Drop 9 immediately after construction.

Figure V-14

Bear Canyon Creek below Martin Drive in Boulder. Drop 9 after flood event. Massive amounts of rock movement within base width of drop. Much of the riprap is scattered downstream.

Figure V-15

Lilley Gulch East of Simms, South of Bowles, (Dutch Creek Tributary), Jefferson County.

Figure V-16

Tributary to Englewood Dam above East Dry Creek Road, Arapahoe County. Example of a failure.

Figure V-17

Tributary to Englewood Dam above East Dry Creek Road, Arapahoe County. Example of displaced rock from failure.

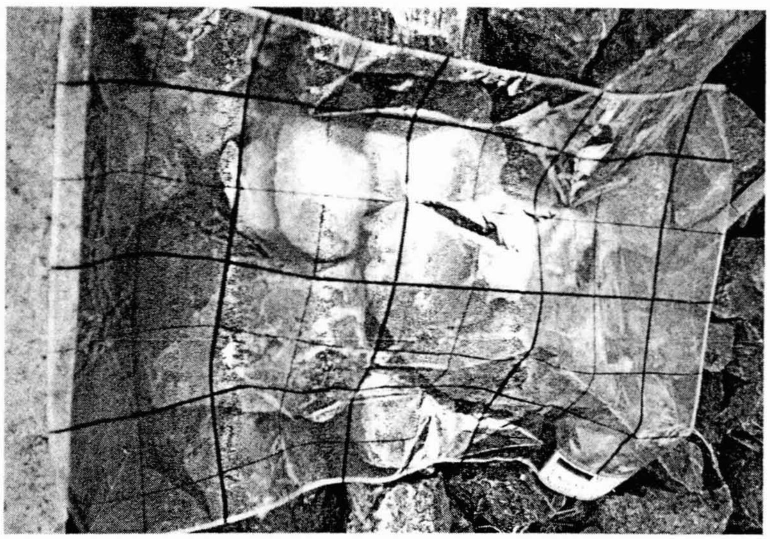


Figure V-18

Tributary to Englewood Dam above East Dry Creek Road, Arapahoe County. 6-inch mylar grid on remaining riprap showing undersized rock (D_{50} spec = 18").

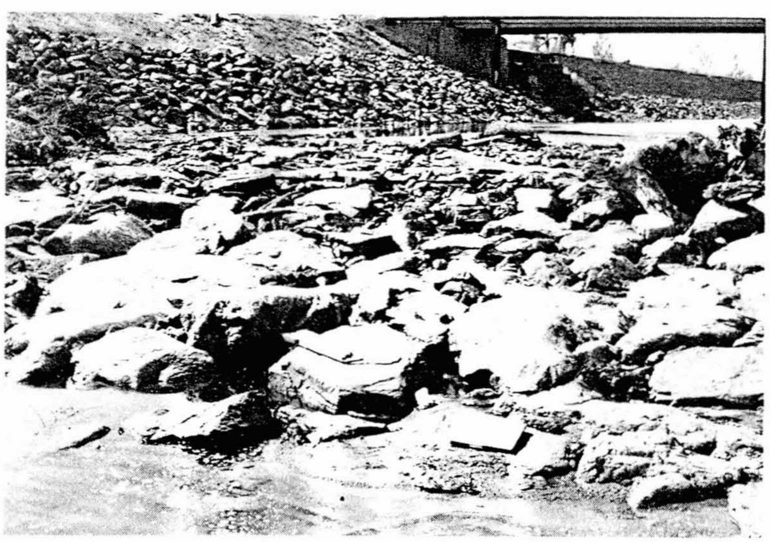


Figure V-19

South Platte River near Oxford in Englewood. Looking upstream at "Derrick Stone" Drop.

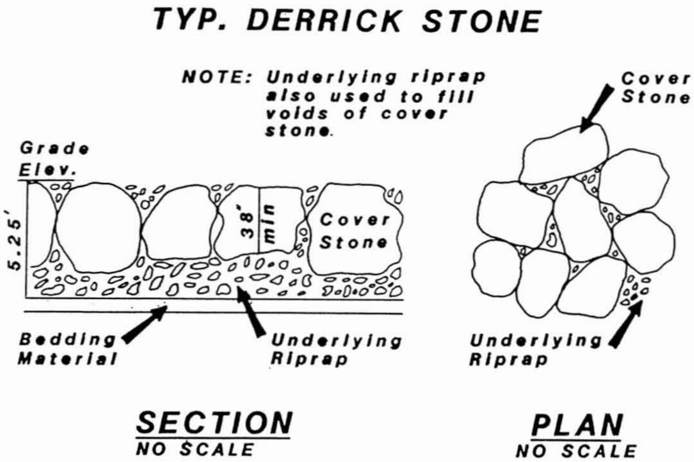


Figure V-20

Derrick Stone (single layer boulders) details by Corps of Engineers.

Figure V-21

Phillips Drainageway, near Yosemite and County Line Road, Arapahoe County. Rock movement occurring. (Rock was originally at crest.)

Figure V-22

Phillips Drainageway, near Yosemite and County Line Road, Arapahoe County. Failure more severe one year later.

Figure V-23

Example gradation test for rock riprap.

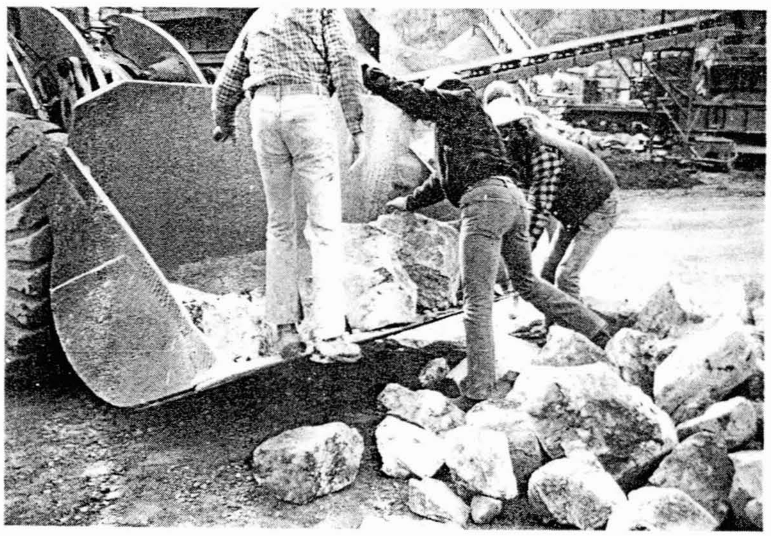


Figure V-24

Example gradation test for rock riprap.

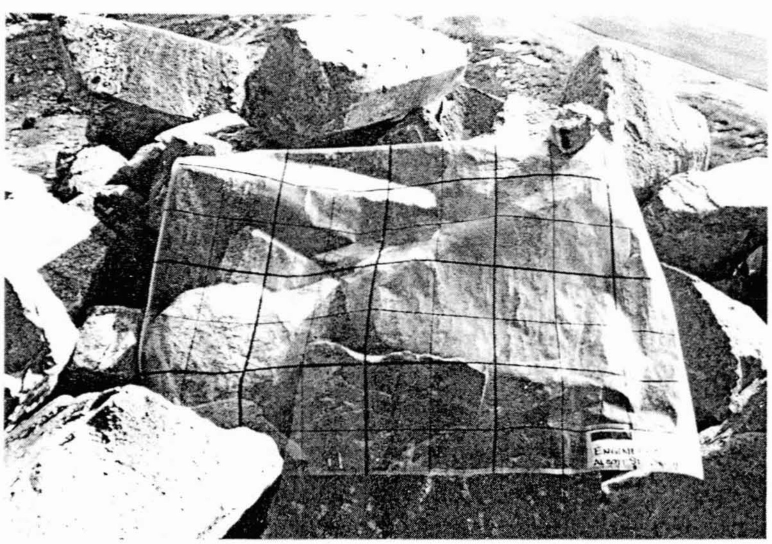


Figure V-25

Grid over sample stockpile.

Figure V-26

Grid over sample stockpile in another area. Note variation from Figure V-25.

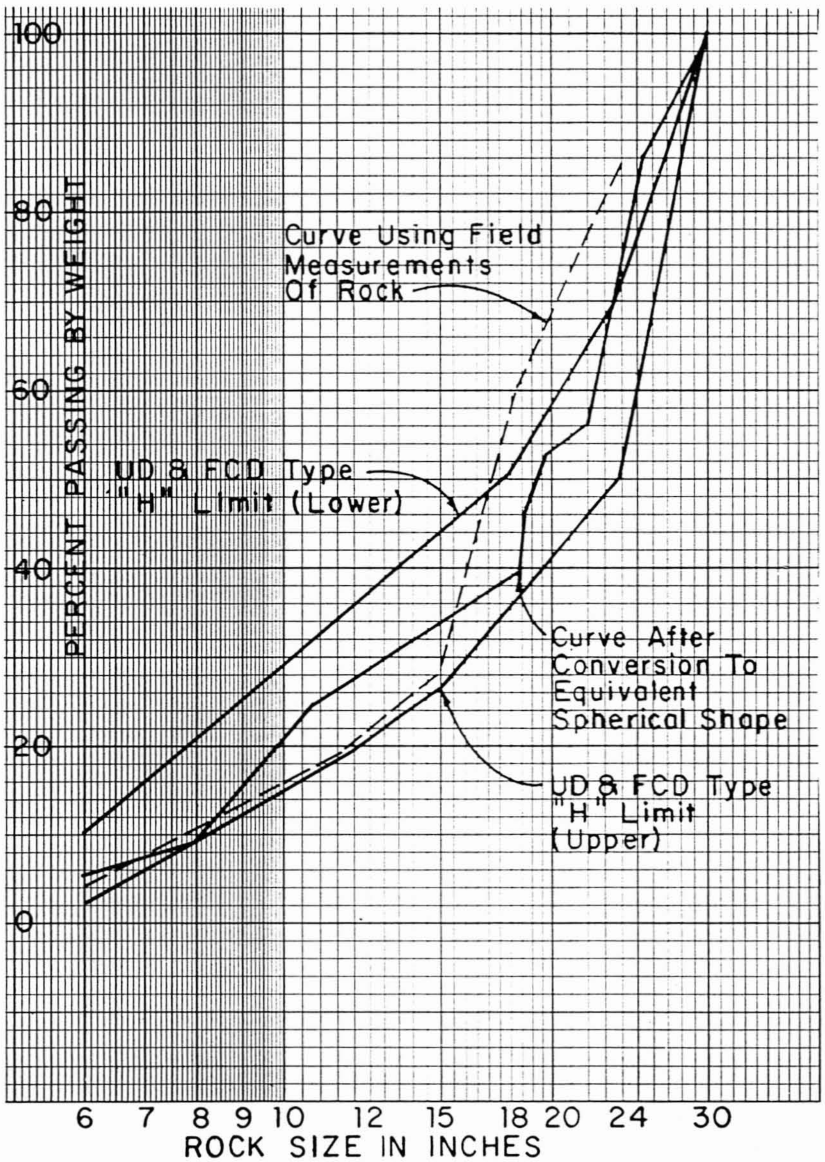
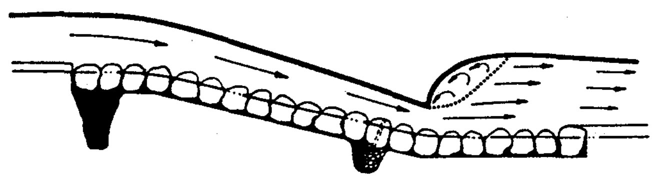


Figure V-27

Example gradation curve resulting from quarry test.



SECTION VI

SLOPING GROUTED ROCK

INTRODUCTION

Sloping grouted rock has a surface hydraulic condition and forces acting upon the structure similar to that of a sloping concrete drop. However, where many of those structures rely on structural concrete, sloping grouted rock relies on its mass to resist the forces, uplift in particular. Seepage control, including conservative cutoff designs and toe drains are essential. The filling of the voids between the subgrade and the rock is essential to avoid piping under the rock and to prevent circulation of surface flow under the rock, thus eliminating lift. Dynamic lift occurs in loose riprap because there is circulation of flow. However, the grout does not necessarily need to go all the way to the rock surface, as hydraulic roughness is generally desirable and the appearance is better when the grout is held 6 to 9-inches lower than the rock surface.

Over the years, it has become clear that one must specify the placement technique. This includes low pressure grouting using a nozzle that can penetrate to the invert, and "pencil" vibrators to allow working grout. Rock of a uniform size that is larger than the grout thickness (not using graded riprap) is important to allow good grout placement to the subgrade.

CASE STUDIES

To attest to the effectiveness of grout, one only has to recognize the countless maintenance repair projects where grout has been used to repair structures and graded riprap which is being displaced. There are also numerous failures, typically where concrete is dumped over riprap. Dr. Simons reports major "blowouts" at structures where uplift pressures were not controlled. The point of the following cases is to illustrate grouted rock used from the inception of a project, and the need for some of the construction improvements described above.

Case 7 - Dakota Avenue Tributary at Depew of Weir Gulch, Lakewood

Figure VI-1 depicts small (both in flow and height) grouted rock drops built as part of a restoration maintenance project. The project has been successful, although the aesthetics might have been improved. The drop itself is formed by large boulders. On the upstream side of the boulders, concrete is placed (contained on one side by the boulders and the other by a form) to provide a cutoff. The rock in the basin is grouted. This could be improved by using boulders larger than the grout thickness and holding the grout to a lower level so that it is not as visible.

Case 36 - South Jefferson County Drainage 6200, near Depew, Jefferson County

This case, depicted in Figure VI-2, is a combination of grouted riprap and loose riprap. The grass covered portions have buried Type L riprap, while the trickle channel is grouted riprap. A concrete cutoff wall was used also. This particular structure is in the backwater of a box culvert, thus it is somewhat protected. Further upstream the drops are being grouted and there are some problems with stability.

Case 46 - Slaughterhouse Gulch Upstream of Prince, Littleton

This is a case of the "battle of grouting graded riprap". As seen in Figure VI-3, the drops are grouted riprap, comprised of approximately 9-inch d_{50} rock. There were extensive problems during construction on grout placement, rock size and grout cleanup. Muriatic acid was used to clean rock after the fact, but it was not satisfactory. Any excess grout has to be washed off immediately.

The plans call for a crest cutoff of larger grouted boulders, but there is no specific dimension of the cutoff depth below the adjacent riprap. Soils are erratic with presence of fine to coarse grained sands. The riprap on the drop and through the basin was shown to have the upper 6-inches grouted (total layer thickness being 1.75 feet), with weep holes. The concern here is that seepage erosion could occur, resulting in a high underflow. Either erosion of subgrade could undermine the structure, or more likely, excessive uplift pressure on the grout surface could occur because the weep capacity would be insufficient.

The basin is depressed at the toe 1 foot, and gradually slopes up to the invert downstream. Thus, extra depth is provided to help with forcing the jump at the toe. The design flow is 1420 cfs. The depressed basin might be further improved by extending this depression elevation to the end of the basin.

Case 47 - Lena Gulch Upstream of Kipling, Wheatridge

Figure VI-4 illustrates a series of drops designed for 2650 cfs. Extensive care was taken with a concrete cutoff wall constructed on caissons and backfilled with imported clay zones upstream and downstream. An engineer was at the site during the grouting of the graded riprap, which was done in a layered approach after removal of the fines. After this job, our personnel resolved not to grout smaller graded rock.

Hydraulically, the basin could be improved by depressing it further through the use of more of the vertical available from the trickle channel. There is a zone of buried graded riprap downstream that will be exposed in events such as the 10 to 100-year flood. One other improvement could be made by putting in obstructions to help dissipate energy and prevent jump washout in the trickle channel. Note the stability of the grass-lined channel and the compatibility of the trickle channel. There has been construction activity upstream, yet stability has been maintained (there is also a reservoir further upstream of the construction).

Case 61 - Lee Gulch Upstream of Windemere, Littleton

This is a drop and dam combination which forms a recreational pond. It was designed by our staff as part of a maintenance project with the District and Littleton. Figure VI-5 illustrates the grouted rock, which in this case was graded rock with all rock smaller than about 18-inches removed. The dam had previously breached and was rebuilt with tight clays. An excavated trench was filled with concrete which was extended to grade to form the cutoff. The rock was placed and a control grid established to check minimum grout thickness. The rock was placed directly on clay subgrade, with weep drain trenches at intervals near the toe. As the grout was held low, it is not very visible. The community was very receptive to the project (including favorable press coverage). We perceive that the project could have been improved by using some larger boulders, and placing rock such that there were exposed horizontal surfaces, in other words, more stepped ledges.

Figure VI-6 illustrates one worrisome maintenance problem. Although quality tests were submitted, the rock varies in quality, with some pieces weathering severly.

The project has experienced several heavy overflows. Seepage at the toe drains is minor.

Case 82 - Clear Creek near Confluence with South Platte River

This project is part of an ongoing maintenance project for a sewer line crossing for the North Washington Water and Sanitation District, undermined by degradation associated with the South Platte River. The photographs here illustrate construction techniques for grouted rock. Figure VI-7 shows the low pressure pump. Figure VI-8 illustrates the large rock with voids open to subgrade. Figure VI-9 illustrates placement and vibration. We noted that if the grout could be held lower it would look better. Figure VI-10 is a closeup view of a grouted area; note that the rock with flat tops look better than the rock with jagged edges or pointed features exposed. Figure VI-11 illustrates satisfactory appearance of the same area from a farther view.

Case 83 - Santa Fe Avenue Dam, Arkansas River, Pueblo

This is an 11 foot high grade control dam and whitewater bypass designed by our firm for the Pueblo Conservancy District. Figure VI-12 illustrates the use of grouted large boulders. The structure uses sheet piles and other special structural and seepage control details. Also, polypropylene fiber reinforcement was added to the grout mix. The grout will be monitored for durability and resistance to abrasion.

Note the good dissipation without a linear hydraulic jump.

CONCLUSIONS

Generally, grouted rock has been successful when large thicknesses of rock and grout are used, and cutoff and seepage control is provided. Many drop designs have attempted to grout design configurations based on sloping riprap designs, but grouting the graded riprap. It is clear that it is an entirely different problem with respect to hydraulics, surface hydraulic forces imparted on the structure, seepage control and uplift. The construction techniques necessary should be different than those for a sloping graded riprap drop.

A key problem noted is the use of a short cutoff wall with loose riprap upstream and/or bedding and ungrouted riprap (under the grouted layer) downstream. This leaves a very short seepage path to the riprap and bedding, which then provides a high capacity path for seepage. Even with the provision of weep pipes, seepage can be such a high flow (from the failure along the short seepage path), that it cannot be relieved and resultant uplift failure can occur. The two most prevalent modes for failure of grouted riprap are uplift and piping/erosion of the subgrade below the riprap. The design and installation can be improved by larger rock (greater in size than the grout thickness), grouting to the subgrade, deeper cutoff and avoiding loose riprap or other free draining materials beneath the grouted rock layer which reduce the seepage length. Toe drains or other specific subdrainage measures should be designated. Placing bedding continuously under grouted riprap should be carefully evaluated. It can be helpful for frost heave, especially for thinner grout layers, but is generally counter productive to controlling seepage uplift pressures. Locating the cutoff upstream of the crest is helpful in seepage cutoff.

Grouting is much more successful and easier to construct if rock larger is in all dimensions than the grout thickness used. Voids between and under the rock are directly accessible and the complete subgrade interface can be grouted. Having rock which is basically 33 to 50% larger than the grout thickness is advantageous for ballast, hydraulic roughness, aesthetics, and weathering. Placing rock with large flat surfaces on the top horizontally is attractive, as well as hydraulically effective. Overall drop slope grades are less important, whereas interlocking and stepping are important to improve hydraulic roughness, dissipation, stability, and minimization of grout volume and visibility. Seepage uplift is critical, and sufficient grout and rock thickness are directly related. As discussed in Section XI, surface hydraulic forces are not very significant (other than the weight of the flow) for grouted rock, where they are paramount for sloping loose riprap.

Recently, polypropylene fiber reinforcement has been installed on several drops. If, as the manufacturer's literature states, the fiber reinforcement serves to increase crack resistance, durability and abrasion resistance, then it may be helpful. These structures should be monitored.

Figure VI-1

Dakota Avenue Tributary at Depew, Lakewood. Small drops using grouted boulder crest (with concrete cutoff) and grouted riprap basin.

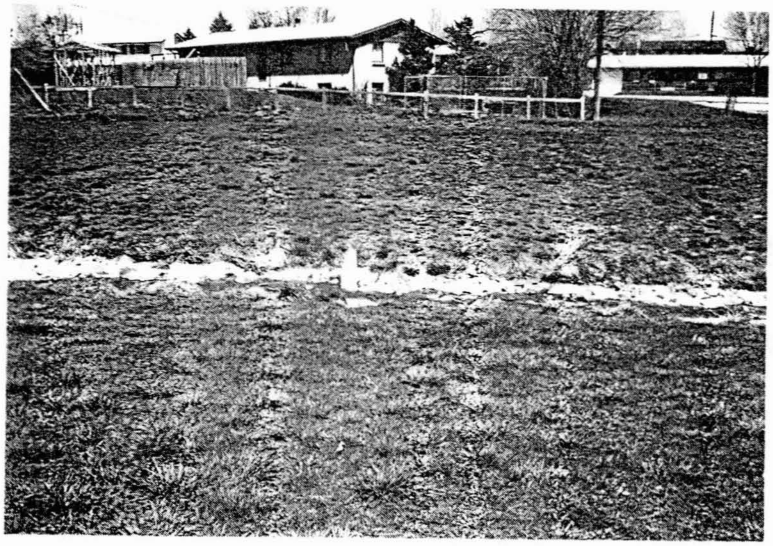


Figure VI-2

South Jefferson County Drainage 6200, near Depew, Jefferson County. Grouted trickle with buried loose riprap (note outline of crest wall).

Figure VI-3

Slaughter House Gulch upstream of Prince in Littleton. Grouted rock drops using riprap are difficult because penetration of voids for the full depth is difficult and results in excess grout on the surface.

Figure VI-4

Lena Gulch upstream of Kipling, Wheatridge.

Figure VI-5

Lee Gulch upstream of Windemere in Littleton. Pond formed by earth dam and grouted rock drop.

Figure VI-6

Lee Gulch, upstream of Windemere in Littleton. Some pieces of rock are experiencing severe weather despite submitted test data.

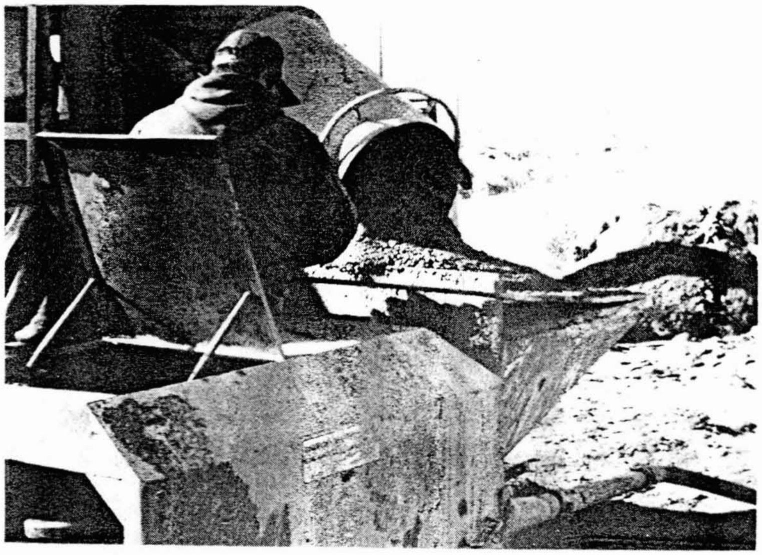


Figure VI-7

Clear Creek near the Confluence with South Platte River, low pressure grout pump.

Figure VI-8

Clear Creek near the Confluence with South Platte River, rock prior to grouting, voids are open to subgrade for ease of grout penetration.

Figure VI-9

Clear Creek near the Confluence with South Platte River. Grouting and vibration with pencil vibrator. Grout is slightly high.

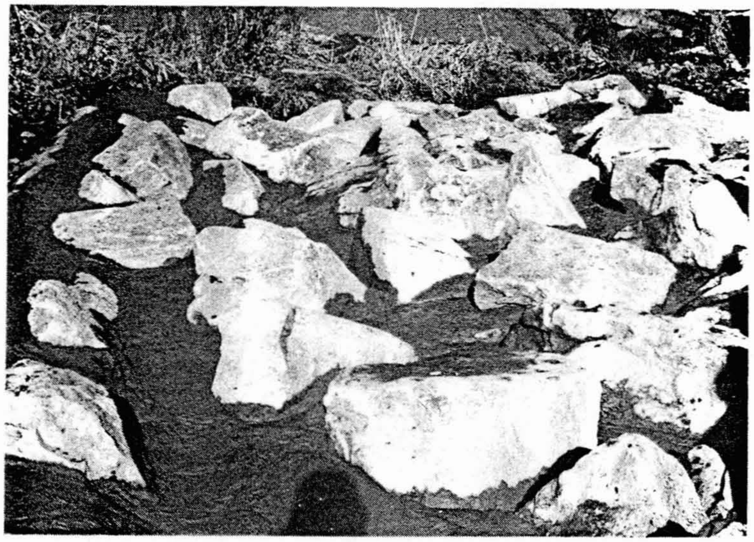


Figure VI-10

Clear Creek near the Confluence with South Platte River closeup of grout area. Grout is slightly high, rock with flatter top surfaces looks better than rock with points and jagged edges.

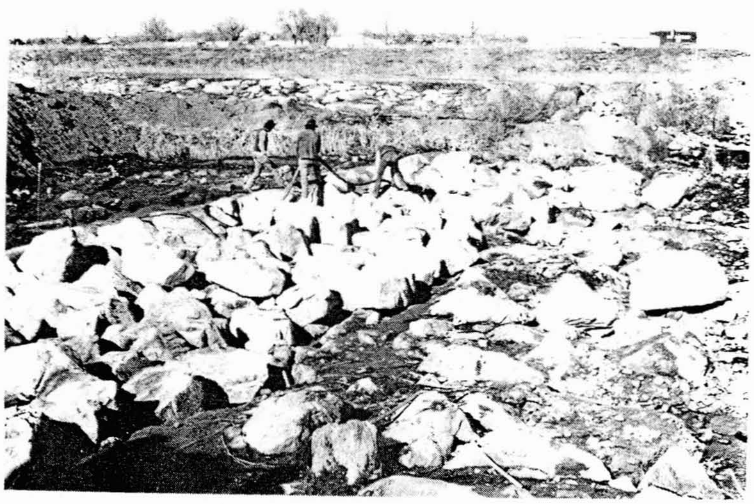


Figure VI-11

Clear Creek near the Confluence with South Platte River. Area in VI-10 is on far side, notice grout not readily visible.

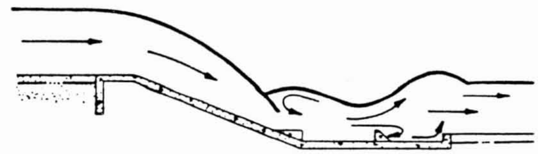
Figure VI-12

Santa Fe Avenue Dam on the Arkansas River in Pueblo, Colorado.

SECTION VII

SLOPING CONCRETE DROPS

AND OTHER SIMILAR HARD BASINS



INTRODUCTION

The hydraulic concept of these drops is to form a conventional hydraulic jump, which dissipates energy by extreme turbulence, usually associated with a reverse current surface flow as the supercritical flow down the face converts to subcritical flow downstream (ref. 7, 10, 17, 34, 53, 54). There are other techniques which place the roller or reverse currents underneath (ref. 20, 28, 43, 61) but their design is more intricate.

As for the conventional drops, there are numerous detailed concepts which have been investigated. Classics among these are the Saint Anthony Falls Sloping Basin, and USBR I, II, IV, V (ref. Chow, Bureas). These drops are suited for different kinds of situations. The Saint Anthony Falls and the Bureas I, IV and V may have limited application to District projects.

The Saint Anthony Falls Sloping Basin and the USBR Basins (with the exception of Type I) all work at techniques to shorten the basin length. In the USBR Basin I no special measures are provided. On the smooth concrete basin it can take considerable basin length to "burn off" enough energy to dissipate the supercritical flow to where a jump will begin, and then more length to allow for the turbulence of the jump. Basin I would be quite expensive because of its length. The other basins require a certain amount of tailwater, which requires depressing the basin, and the use of baffles and other shapes/profiles to allow shorter basins, related dissipation, and control of troublesome wave patterns. There are also various construction techniques such as soil cement and rollercrete. These types of configurations may provide hydraulic profiles of various types.

CASE STUDIES

Grass-lined channels typically involve low unit discharges and low Froude numbers. The depressed basins may be troublesome with regard to maintenance and nuisance conditions. Therefore, their use has been limited. Following are a few cases investigated in the Metropolitan area.

Case 48 - Massey Draw Upstream of Carr

Figure VII-1 depicts this drop, which is 21 feet high with the lower end submerged in a pond. The basin width tapers to a smaller width upon entering the pool. The design flow is 2085 cfs and the drop appears to be generally satisfactory. It certainly fits with the pond. The baffles on the face were provided to prevent its use as a bicycle ramp, which basically seems questionable considering that the slope is 2:1 (maybe to prevent use as a slide).

There is not sufficient provision for a trickle channel, and aggradation is being experienced as seen in Figure VII-2. This problem is also associated with a sill on the crest.

It was also noted in the file that the entire project was not accepted for maintenance because of lack of a trickle channel on the project.

Case 49 - West Harvard Gulch between Tejon and Zuni, Englewood

This is an interesting design which uses a 2-year storm sewer to carry frequent flows, and a grass-lined channel with concrete drop to convey the 100-year flow of 1000 cfs. Actually, there is concrete rubble riprap buried downstream because clearly the basin is too short to contain the jump as seen in Figure VII-3. The park setting is nicely maintained by the City of Englewood.

Case 50 - Niver Creek just upstream of Confluence with South Platte, Adams County

This is a modified USBR Type III drop. The baffles on the face have been moved up because the designer was concerned that they would be submerged and ineffective. Its use has been extrapolated for a Froude number less than 4.5 which is the normal Bureau limitation. Also, riprap has been used above walls that were shortened to economize. The design flow was 2700 cfs.

Figures VII-4, -5, and -6 are various views. Clearly there are scouring problems downstream, but it appears that most of this is due to headcutting caused by Platte

River degradation. Regardless, the concern is that the tailwater in the basin would then be lower and the jump could wash out. No provision is made for transition to the trickle channel downstream, riprap has been moved to form a secondary drop downstream and high walls have no railing or fences for safety provisions.

Case 53 - Unnamed Creek near Bates and Flanders, Aurora, Colorado

This is a recently constructed drop, designed for a flow of 5800 cfs. Figures VII-7, -8 and -9 depict the ten foot drop, which is the Saint Anthony Falls type. Figure VII-7 shows a general perspective. Note that the rock upstream is somewhat larger than downstream, depending on location. There is no provision for the trickle channel upstream and we suspect that aggradation may occur. Figure VII-8 shows weeds and riprap in the basin. Downstream, Figure VII-9 shows a nice transition to the trickle, but much larger rock should be used with some provision to dissipate the jet that will break through this area. The soils appear to be a silty sand with provisions made for seepage control. The downstream bed appears to be controlled by the road crossing, otherwise a baffle chute would have been a preferable choice. The literature researched did not provide any guidance on the effect of sloping abutments used on this project.

CONCLUSIONS

There may be applications where sloping concrete drops are advantageous, but generally speaking, other drops such as baffle chutes or sloping grouted rock appear to be more appropriate for District conditions. The basin depths required do create maintenance and nuisance problems. The guidance provided by the literature is clear and relatively easy to use, but the implementation is often difficult or impractical for District grass-lined channels. This basically has to do with providing basin depth without creating a maintenance problem, less flexibility in adapting to varying bed conditions and generally low Froude numbers associated with drops in grass-lined channels.

Figure VII-1

Massey Draw upstream of Carr, Jefferson County. Sloping concrete drop with 21 ft. drop, lower end submerged in pond.

Figure VII-2

Massey Draw upstream of Carr, Jefferson County. Upstream of concrete drop, aggradation occurring.

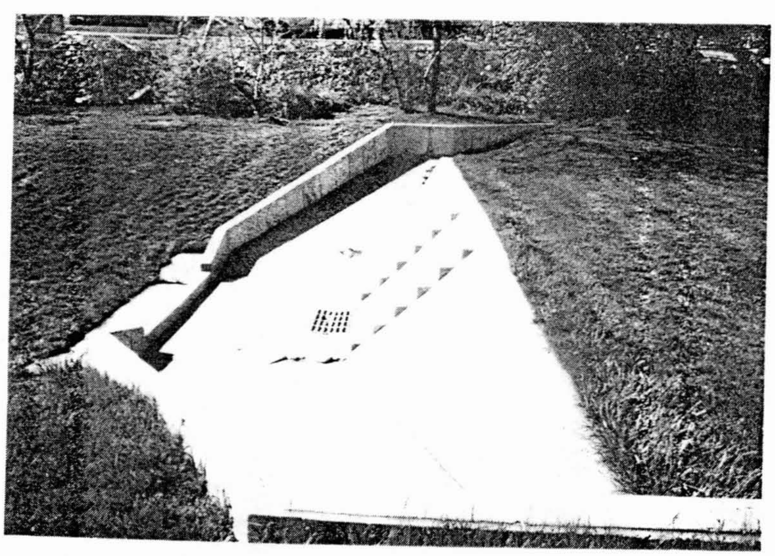


Figure VII-3

West Harvard Gulch between Tejon and Zuni, Englewood. Flows up to the 2-year are carried in a storm sewer. Buried rubble is used downstream of the concrete basin.

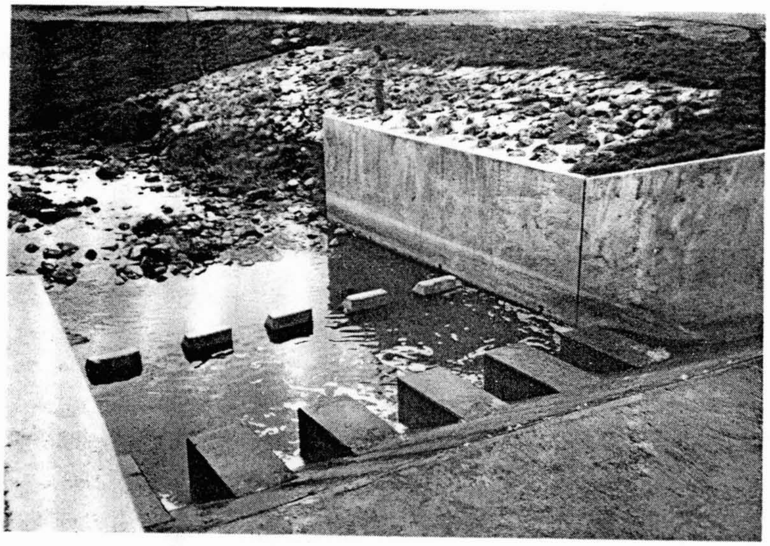


Figure VII-4

Niver Creek just upstream of the South Platte River, Adams County. Modified USBR III Basin, baffles on slope have been moved up and sidewalls shortened with riprap above.

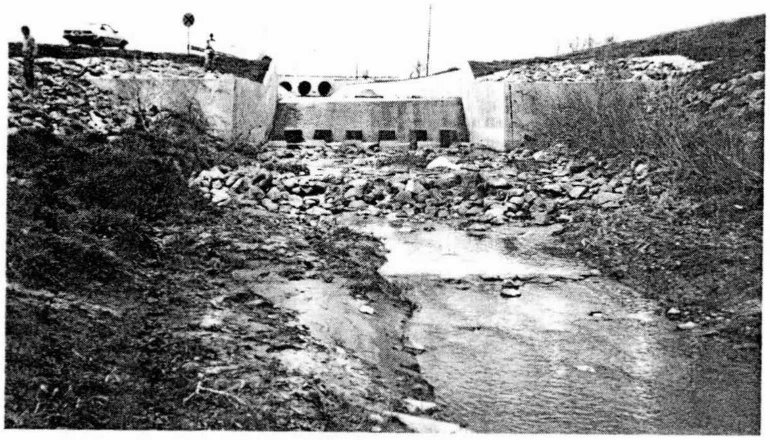


Figure VII-5

Niver Creek just upstream of the South Platte River, Adams County. Upstream view looking at secondary drop formed by displaced riprap.

Figure VII-6

Niver Creek just upstream of the South Platte River, Adams County. Overview of headcutting and instability downstream. If related tailwater becomes insufficient, jet will wash downstream.

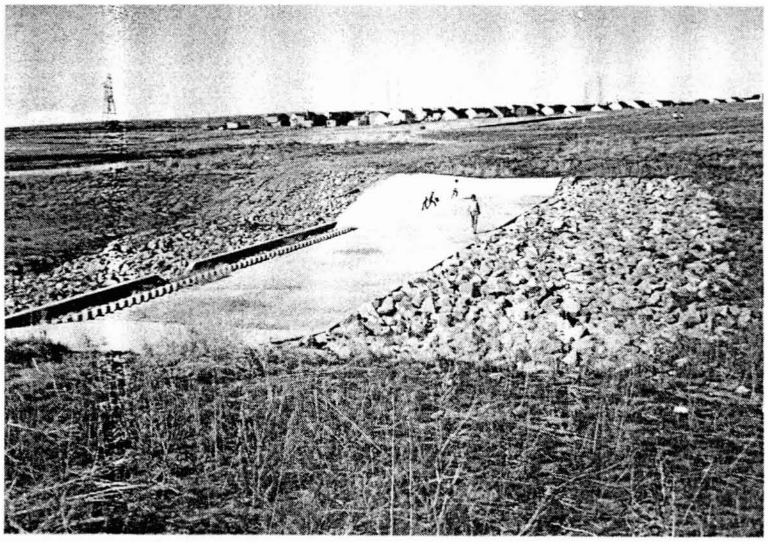


Figure VII-7

Unnamed Creek near Bates and Flanders, Aurora. Overview, no trickle provisions upstream. SAF sloping drop.

Figure VII-8

Unnamed Creek near Bates and Flanders, Aurora. Basin condition is a nuisance.

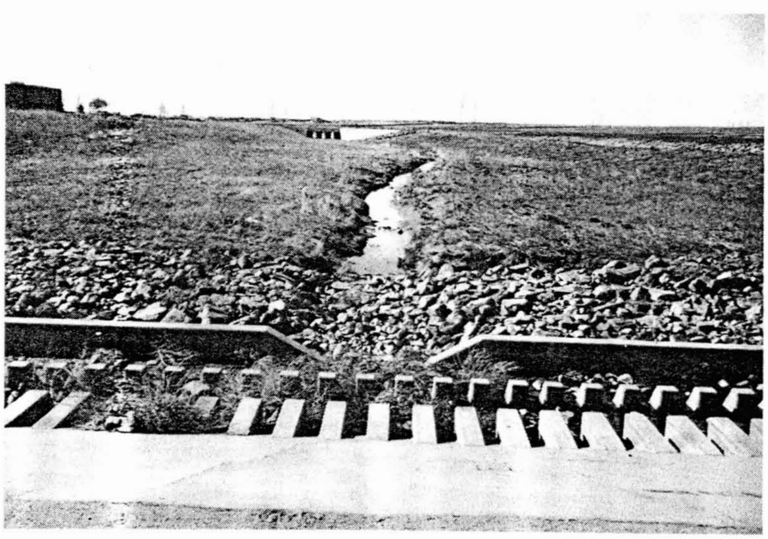
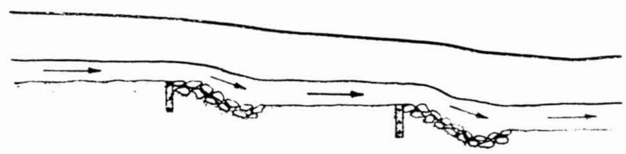


Figure VII-9

Unnamed Creek near Bates and Flanders, Aurora. Downstream trickle provision made, but rock is smaller and extra features need to dissipate jet in this location.

SECTION VIII
LOW FLOW EROSION CHECKS AND CONTROL MEASURES



INTRODUCTION

With the advent of flood plain management and regulation, developers have often preserved the flood plain or made only minimal intrusions. Unfortunately, urbanization creates more frequent and sustained flows. It is not uncommon for waterways to subsequently experience 3 to 6 feet of erosion, with the very real possibility of the entire floodway receiving serious damage and endangering property. Put another way, the overall flood plain may be stable and able to resist major flood events, but the trickle/low flow channel has exposed soft, wet soils that are susceptible to erosion, and stable only when the channel invert has a very flat slope. These situations can also occur in grassed waterways, many of which have wide shallow flows and are below developed areas.

The basic strategy is to determine the stable slope and configuration for a variety of frequent events, with particular emphasis on the dominant discharge (mean annual or 2.33 year flood). Evaluation of the soils, bed materials and transported materials is part of this evaluation.

The common technique is then to construct a series of small drops which then provide control points and establish bed slopes. With this control provided, erosion is still likely, but its extent is minimized. Other options which are used, depending on the situation, and in various combinations, include trickle channel lining, toe riprap, control sills across the flood plain, revetments, and groins.

CASE STUDIES

There are numerous examples of check structures. Many can blend with, or are hard to distinguish from, regular drop structures. This is appropriate as they in effect must control both low flow channels and the major floodway.

Case 8 - Bear Canyon Creek, upstream of Broadway, Boulder

Figures VIII-1 and VIII-2 depict the case where it is difficult to distinguish between a check structure and a drop structure. There is little capacity before flow is over the abutments, so we categorized them as check structures. The structures have had to be rebuilt several times and in 1985 grout work was added to prevent headcutting by piping through the voids. We suspect that the rounded boulders were troublesome until grouted. Judging by the stream slope, we suspect that the drops should have more capacity, as higher flows will have very erosive velocities.

As seen in Figure VIII-2, a notable aspect of these drops is the depression in the basin downstream that dissipates the energy and allows quiescent flow downstream. Note also that the crest had to be widened to achieve seepage cutoff.

Case 10 - Little Dry Creek in Arvada

As part of a rehabilitative maintenance project, check structures and other improvements were designed to stabilize serious erosion of the trickle channel which had enlarged to major scoured out sections. Rock check structures were utilized after determination of the stable slope as evidenced by Figures VIII-3.

Although successful for stabilizing the channel, problems occurred with the checks themselves in terms of endcutting and piping erosion. The structures were grouted under a District maintenance project, but there are still problems with seepage and endcutting, as seen in Figure VIII-4. Though limited by funds, our thought in hindsight, is to do much more in seepage cutoff upstream of the crest and extending the cutoff laterally into the bank, along with the addition of more bank rock work.

Case 22 - Sanderson Gulch between Lipan and Tennyson, Denver

Figure VIII-5 illustrates grouted Type L checks used in this project on some locations. Evidently, the upstream edge was thickened, but some seepage and end erosion has occurred. The channel upstream is apparently stabilized.

Figure VIII-6 illustrates loose riprap checks, which have also stabilized the channel but are experiencing adjacent scour problems.

Case 23 - East Harvard Gulch east of University, Denver

Figure VIII-7 is presented mainly to illustrate what happens with "sugar coated" grout, or in this case, shotcrete. Without complete penetration of the voids, support is undermined. Also, the shotcrete layer is so thin that it has no integrity.

Case 65 - Little Dry Creek, Cherry Hills Country Club

Storm runoff spills from the Highline Canal and increasing low flows from the urbanizing area upstream resulted in degradation of several feet in the golf course. The golf course installed check structures and some bank improvements/trickle channel relocations for a limited project budget. In a second phase, the Urban Drainage District further stabilized the banks and improved the check structure.

Figure VIII-8 illustrates a typical check structure, and Figure VIII-9 depicts some of the bank stabilization measures.

CONCLUSIONS

Low flow checks and associated erosion control techniques can be effective in stabilizing grass-lined channels and flood plains. The application and sizing is complex because of the need to address a wide range of flows. Although the checks may stabilize low flows, the checks themselves may be in jeopardy for mid-range flows as water goes around the check abutments.

Extensive care is needed with seepage cutoff and abutments that key far back into areas that are less likely to be damaged during high flows. Care should be taken to have a depressed stilling area to avoid a secondary drop at the end of the drop. In any case, ongoing maintenance of check structures will be likely and should be considered in the design so later repairs are practicable.

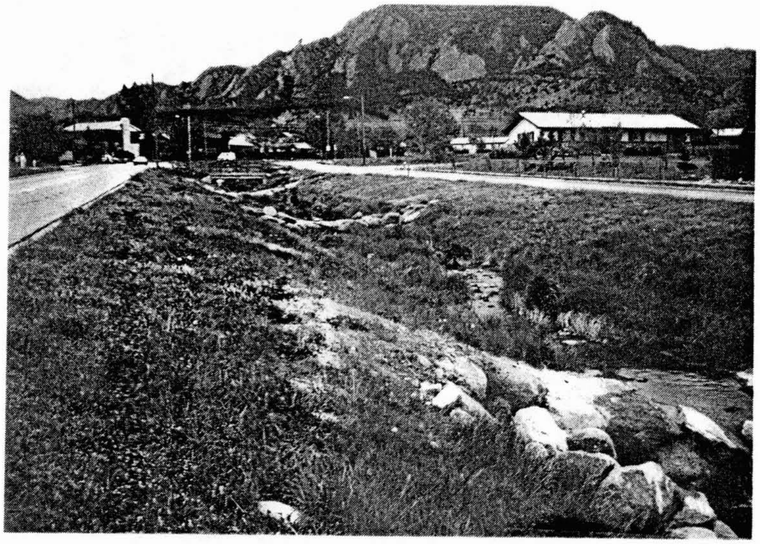


Figure VIII-1

Bear Canyon Creek above Broadway in Boulder. Grouted boulder check structure.

Figure VIII-2

Bear Canyon Creek above Broadway, Boulder. Note depressed basin downstream for good energy dissipation, problems with scour at abutments.

Figure VIII-3

Little Dry Creek in Arvada. Stabilization of grass channel/flood plain with low flow check structures.

Figure VIII-4

Little Dry Creek in Arvada. Some low flow checks experienced end erosion and excessive seepage even after grouting.

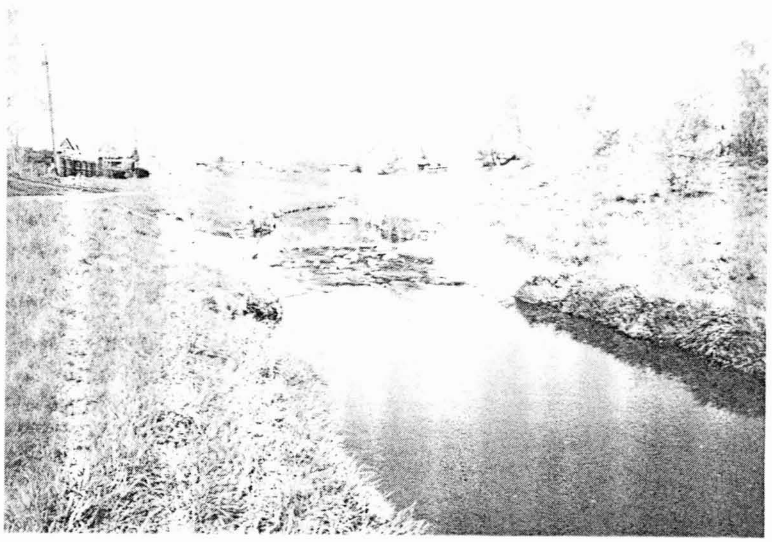


Figure VIII-5

Sanderson Gulch between Lipan and Tennyson. Grouted check structure stabilizing channel.

Figure VIII-6

Sanderson Gulch between Lipan and Tennyson, loose riprap check experiencing slightly more problems but stabilizing channel.

Figure VIII-7

East Harvard Gulch east of University, Denver. Failing shotcrete trickle drop.

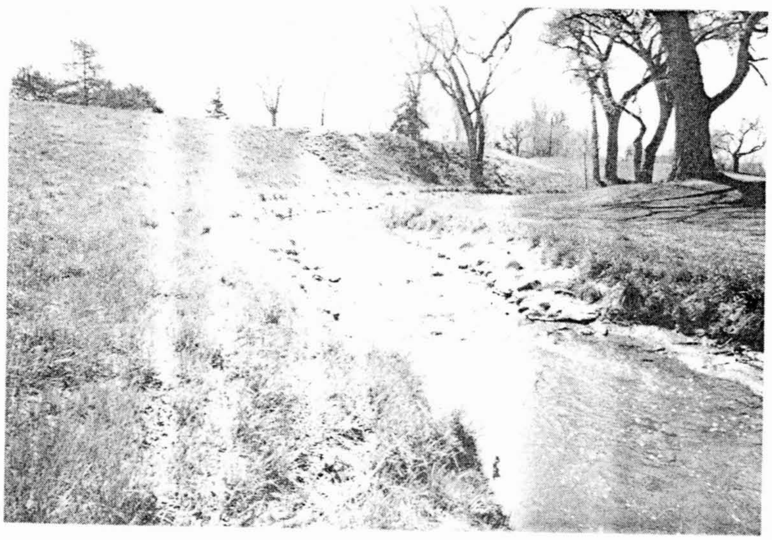


Figure VIII-8

Little Dry Creek at Cherry Hills Country Club. Typical check structure.

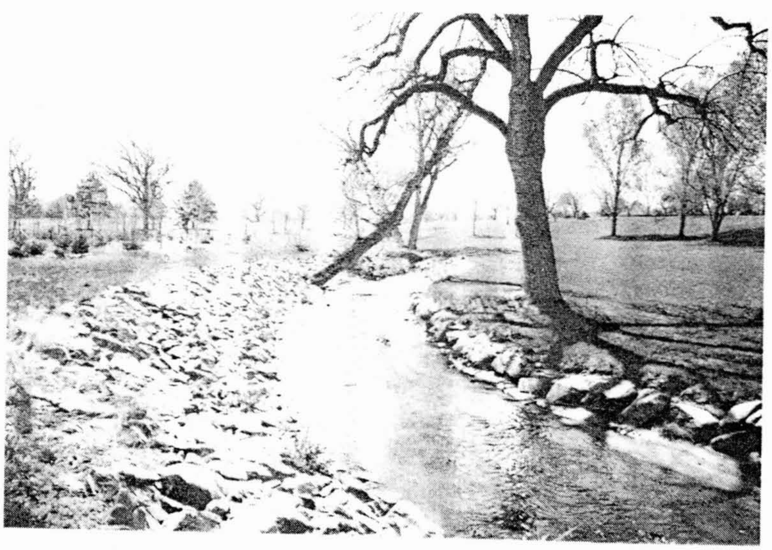
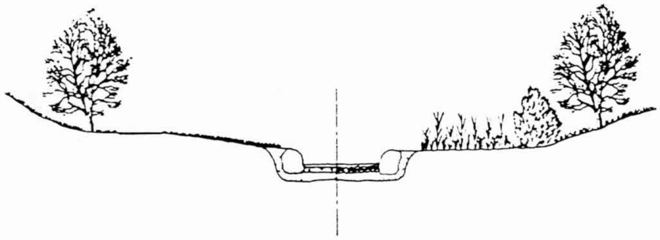


Figure VIII-9

Little Dry Creek at Cherry Hills Country Club. Typical low flow bank improvements.

SECTION IX
NOTES ON THE TRICKLE AND MAIN CHANNEL



INTRODUCTION

In the process of reviewing the many drop structures in the field and the literature, we observed many influences and interactions between drop design, trickle channels and the main channel layout. The configurations of each are changed, sometimes dramatically, by the interdependancies, mismatches with the environment (e.g. high sediment production), and the influence of maintenance practices.

There is no perfect solution. For example, preservation and creation of wetlands, which is desirable for environmental and water quality reasons, can lead to aggradation and reduction in conveyance capacity. The following discussion argues for having the upstream trickle channel penetrate through the crest of the drop structures in order to lessen aggradation problems. This action will cause some problems with the drop structure. Of course, economics has a great influence in design decisions, with the case often being the serious consideration of initial capital costs alone (and thus the reduction of effort in the trickle channel).

TRICKLE CHANNELS AND UPSTREAM AGGRADATION

Many of the drops investigated have: 1) level crests with little or no provisions for a trickle channel; 2) the trickle channel discharging into riprap upstream of the crest, with drainage provided only through the voids in the riprap and notches in the crest; or, 3) small pipes through the crest. The result of this has been aggradation upstream, presumably caused by sedimentation associated with the frequent, low discharge that spreads out and travels at low velocity in the main channel bottom. There are numerous examples of up to 12-inches of deposition, and quite a few in the order of 12 to 24-inches.

In these cases, a trickle or low flow channel is created which is generally on the order of 12 to 18-inches deep and has a width seemingly dependent on the general size of the watershed, degree of development, and factors such as spills from irrigation ditches. The sides of these channels are generally near vertical and barren, with adjacent horizontal surfaces that are heavily vegetated. In some cases, a heavy grass sod has been created and is somewhat reasonable to maintain. Also, the aggradation appears to stabilize after an adequate trickle channel has been created. (Sanderson Gulch, East Harvard Gulch, Weir Gulch below Alameda, Niver Creek at the Baffle Apron). However, this is an observation supported by general principals of sediment transport and hydrology, rather than a thoroughly supported and scientifically investigated hypothesis.

Nevertheless, it appears quite sensible to create a trickle channel from the beginning, on the order of 18 to 24-inches deep. There are several drainages that now have enough aggradation to be concerned about the loss of hydraulic conveyance.

The basic main channel configuration is also of concern. The design configuration typically utilized is a trapezoid with a bottom that at most has a cross slope of 2 percent, and main bank side slopes of 4:1 and typical depth of 3 to 4.5 feet. It appears that in higher discharge ranges, say greater than 1500 cfs, aggradation occurs because the lower flows are spread out. This is hardly a new problem. Man has searched for stable, self maintaining/cleaning conveyance sections since the advent of man's waterworks (ref. 10, 45, 47, 48, 49). Our observation has been that in some cases deeper channel sections have less trouble with aggradation. Thus, we see the need for investigating modified design guidelines that would encourage deeper flows for higher discharges, or more scientifically, would convey a wide variety of flows, without erosion or sedimentation. The deeper flows may also be used to create sufficient tailwaters for upstream hydraulic jumps.

THE TRICKLE THROUGH THE DROP

Care will need to be taken with regard to the hydraulic analysis, as the deeper flow through the crest at the trickle will need to be addressed. This is described in Section X and XII.

DESIRABLE TRICKLE CHANNELS

The most satisfactory trickle channels provide good lateral drainage, are adequately protected against erosion during high flow, have minimal sedimentation during low flow, provide a reasonable transition between zones of dissimilar velocities, and stabilize the main channel. In this regard, adequate depth must be provided, as well as, appropriate transition to the adjacent channel bottom.

The shallow concrete pans, or pans with small curb-like transitions, have not always proven satisfactory. This is because of the poor lateral drainage (seepage has to go up and over the concrete edge) and frequent wetting from minor flows, both of which leave the soils wet and in a weakened condition, as well as killing the grass.

The designs using larger boulders to form the edge (backed by riprap and bedding for good drainage) and inverts comprised on concrete or combination riprap/soil are preferred. All riprap designs are generally reasonable depending on problems with vandalism and rock quality. They are depicted in Figures IX-1, -2 and -3. Concrete designs are workable, particularly those which have good provisions for depth of flow, good subdrainage where seepage flow can be transmitted through the wall to the invert of the channel, and the dissipation of differential velocities between concrete and grass linings.

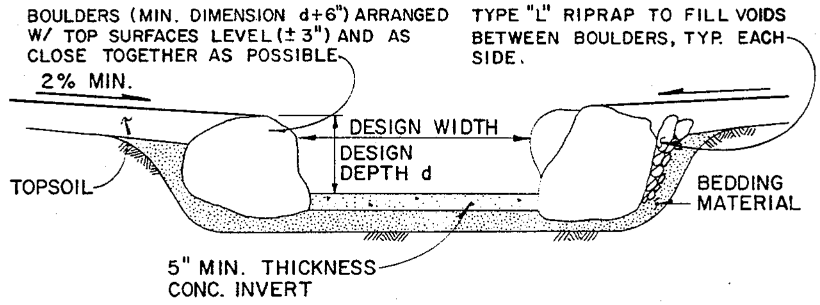


Figure IX-1

Trickle channel with boulders edge and concrete invert.

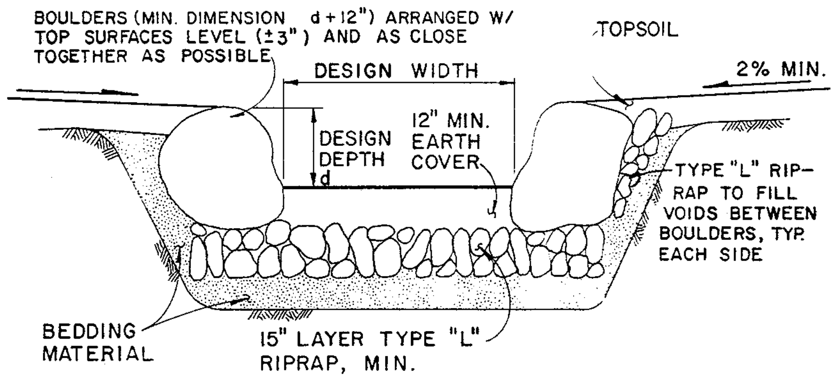


Figure IX-2

Trickle channel with boulder edge and rock/soil invert.

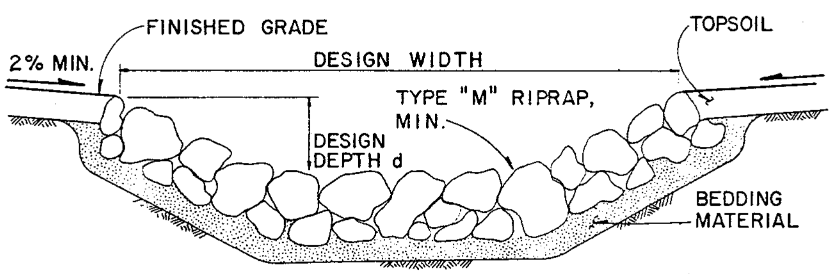
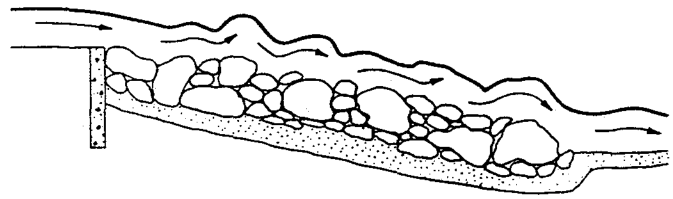


Figure IX-3

Rock riprap trickle channel.



SECTION X

REVIEW OF ROCK SIZING

INTRODUCTION

Clearly there are major problems with riprap drops in the Drainage District. A significant portion of the problem has to do with materials quality control, gradation, construction placement, and the lack of measurable or practical standards of quality control.

However, the need also exists for improving the design standard. The present design standard is based on a safety factor of approximately 1.0. This should no longer be acceptable based on the magnitude of problems experienced, quality control problems, and the highly fluctuating and significant force fluctuations relative to a highly varying size of material. Also, the design needs to consider actual hydraulics on the main crest and down the drop, and incorporate considerations for the trickle channel.

GENERAL LITERATURE REVIEW

Early research by Isbash (ref. 21) in the 1930's, considered flow over dumped rock dams which appears to be applicable to this problem. However, these dumped rock dams apparently had no particular crest control, unlike the Denver drops. On the other hand, it has value because apparently it was based on prototype situations rather than being totally based on models. There is relatively little research on riprap and boulder drops for grass-lined channels that are similar to the situations faced in the Metropolitan area. However, there is a relative abundance of research into the fundamentals which would be needed to even deterministically approach the problem. The topics include: velocity distribution (ref. 3, 17, 45, 48, 62); roughness (ref. 2, 3, 10, 17, 45, 48, 49); shear stress and allowable shear stress for noncohesive materials (ref. 2, 3, 10, 19, 37, 38, 42, 45, 47, 48, 49, 50, 52, 55, 65); and shear stress and allowable shear stress for cohesive and vegetation covered surfaces (ref. 10, 13, 45, 49, 51, 55).

Recently, there has been research regarding critical shear stress (Shield's parameters) for larger particles (ref. 4, 42, 48, 65); and roughness/flow characteristics of flow on riprap surfaces (ref. 4, 12, 47, 48, 51, 52, 57); for sizing channels and rock linings including effects of bends, and channel sections (ref. 3, 13, 26, 37, 38, 45, 48, 49, 56, 60); for sizing channels and rock linings to also include effects near channel transitions, and energy dissipation structures (ref. 1, 5, 7, 12, 13, 14, 19, 24, 25, 29, 34, 40, 42, 47).

There are several investigations which explore plunge pools below free fall crests and culverts, and empirically derive relationships on rock sizing and interrelated scour hole dimensions (ref. 6, 8, 16, 19, 47).

The Soil Conservation Service (SCS) has prepared guidance on sizing channels with the primary purpose of making grade changes at subcritical flow (ref. 32, 56).

The SCS, Army Corps of Engineers (COE), and the Bureau of Reclamation (USBR), have done extensive work on reinforced concrete (or equivalent sheet pile) drop structures that can work with grass-lined channels (ref. 1, 5, 13, 32, 34, 56). The SCS has done a lot of work with grassed waterways for erosion control (ref. 55), whereas the COE works more in the area of flood control for urbanized areas (ref. 12, 13).

Recently, investigations on the overflow of embankments, dams, and levees has been completed. These investigations are oriented toward the prediction of scour location, amount of scour, and the breaching and effectiveness of various control measures. It appears that there should be valuable data which can be used to document stable riprap drop design, however, the work thus far is oriented toward the immediate problem of embankment overflow erosion (ref. 9, 15, 27, 35, 36, 39).

Work has also been done to explore the mechanics of movement, experiments have been aimed at measuring pressure distributions and fluctuations, as well as, drag and lift coefficients (ref. 45, 48, 65). These experiments may lead to a more analytical approach to the design of riprap (ref. 42, 60).

The study that the Urban Drainage District and Stevens relied on for their reasonable approach to sloping loose riprap drops was by Smith and Murray (ref. 52). This was a model and analytical study of sloping drops where flow over a crest arrives at supercritical flow, and then transformes through a hydraulic jump to subcritical flow. It is clearly an excellent study and basically applicable to this problem. The key weaknesses of applying this study are related to the facts that: 1) it did not investigate the relationship to a grass-lined channel, and 2) that it investigated slopes from 4 to 7 percent, where the District uses drops with slopes of up to 25%. This study will be reviewed further in this section.

Also, more recent studies are indicating that roughness characteristics under prototype conditions for the typical steeper slopes are generally changed to higher values for the shallower relative depths of flow, such as that which occurs on the face of drops (ref. 4). In addition, critical shear stresses at higher Reynolds numbers and lesser relative depths may be larger (ref. 4, 52, 65).

Another key study by the Corps is "Stabilization of Stream Beds with Sheet Piling and Rock Sills" (ref. 23), which investigates drops which are submerged by tailwater to an elevation greater than the critical depth at the crest. This study, which also included a physical model study, is valuable for rock sizing relationships, hydraulics, and also because it introduces a practical way to place large rock.

There are several other important papers; particularly by Little (ref. 24, 25), which give guidance on problems with low drops such as effective energy dissipation, and troublesome perpetuation of waves downstream. They give guidance on critical depth, drop height, and Froude numbers which are practical numbers that can be evaluated by the designer. Facilities are investigiated that mitigate the problems.

It should be very clear that the general area of riprap and the specific topic of sloping riprap drops are complex. In the case of sloping drops, the significance and relationship of many of the parameters are not satisfactorily understood. The utilization of riprap drops should be approached with a great deal of care so that the designer understands the potential problems, ramifications, and risk possibilities of riprap and rock for sloping drops.

HIGHLIGHTS OF KEY REFERENCES

There are several references which have information useful to the evaluation of riprap drop structures, particularly for grass-lined channels, as utilized in the Denver Metropolitan area. These are presented in an order which builds the analysis approach utilized in evaluating Denver riprap drop structures.

Simons and Senturk, Sediment Transport Technology (ref. 48)

This reference presents a very thorough discussion of the theory and practical approaches to the problem of sediment transport, and in the case at hand, the stability of riprap. Drag, lift, location within a channel, gradation, angle of repose, and numerous riprap sizing methods are reviewed.

Shear stress imparted on the bed of the stream by the water is generally defined as:

$$\tau = \gamma RS \qquad X.1$$

where

γ = Specific Weight of Water

R = Hydraulic Radius

S = Slope

The force resisting movement is essentially weight for noncohesive materials, and the Shield's Parameter, F_* is the ratio between these at the point of incipient motion. The critical shear stress and hydraulic radius is noted by subscript c:

$$F_* = \frac{\gamma R_c S}{(\gamma_s - \gamma)\, d} = \frac{\tau_c}{(\gamma_s - \gamma)\, d} \qquad X.2$$

where

γ_s = Specific Weight of Water

d = diameter of the resisting rock

In effect, the Shield's parameter is perceived by this investigation as a lumped factor which considers lift forces, drag forces, and the fluctuating nature of the pressures involved. The Shield's Diagram is presented, which gives a variable relationship for F_* as a function of the Reynolds Numbers, which is typically defined as:

$$R_* = \frac{U_*}{\gamma_d} \qquad \text{X.3}$$

where

$$U_* = (g\ R\ S)^{1/2} = \text{Shear Velocity} \qquad \text{X.4}$$

γ_d = kinematic viscosity

The fundamental problem discussed in the reference, and which is of paramount importance here, is assigning a Shield's Parameter. They refer to Meyer-Peter and Muller suggesting a value of .047, but note that "0.06 is most generally accepted". For Reynolds numbers greater than 500, the Shield's Parameter has been generally regarded as a constant. However, as will be shown later, several references and work herein points out that there is apparent variability. They also note that "the upper limit of R is subject to discussions". The context of the discussion is for general channel riprap sizing, as opposed to drop structures.

One critical problem is the determination of incipient motion. Different researchers use varying approaches. This results in the scatter of data apparent on a Shield's diagram or the wide variation in design diagrams which, for example, portray required d_{50}'s for critical tractive force (Figure X-1). Many of the efforts extrapolate laboratory results to determine flow levels (shear) with no sediment movement. Others may have definitions which allow some movement. Figure X-2 is a superimposed plot of the Shield's Diagram with Gessler's work, which refined the diagram. Other research has added information which will be discussed later.

A useful diagram is Figure X-3, it illustrates angle of repose for dumped riprap which is of importance to a sloping rock drop. There is good guidance in ref. 48 on riprap gradation, although in a later reference (ref. 51), there are suggestions to reduce

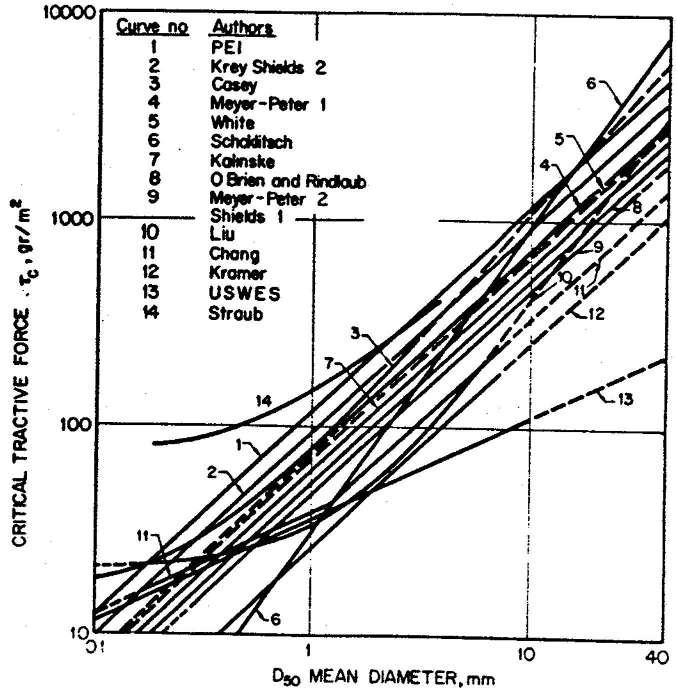


Figure X-1 Comparison of Critical Shear Stress as a Function of Grain Diameter (from Ref. 48)

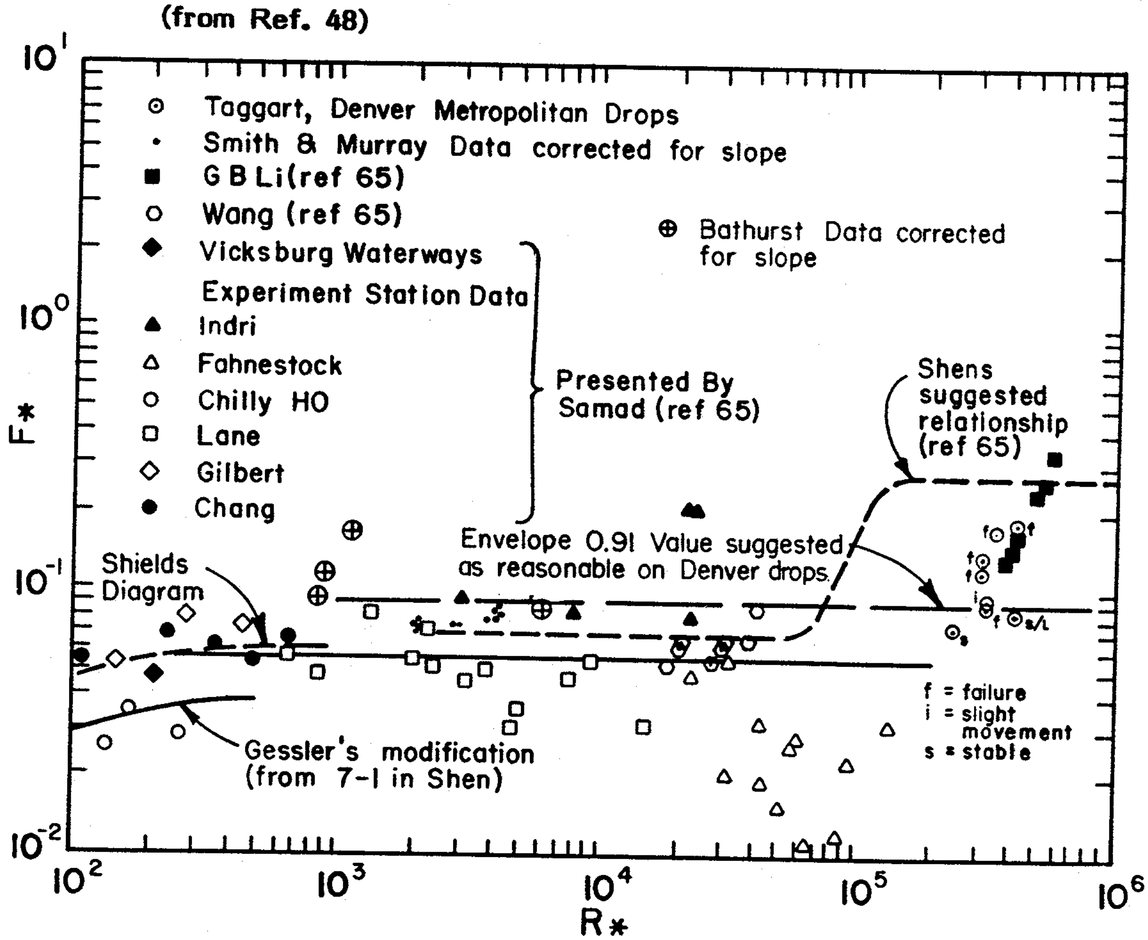


Figure X-2 Extended Shields Diagram (base taken from Samad ref. 42, ref. 65 added, and other data developed herein)

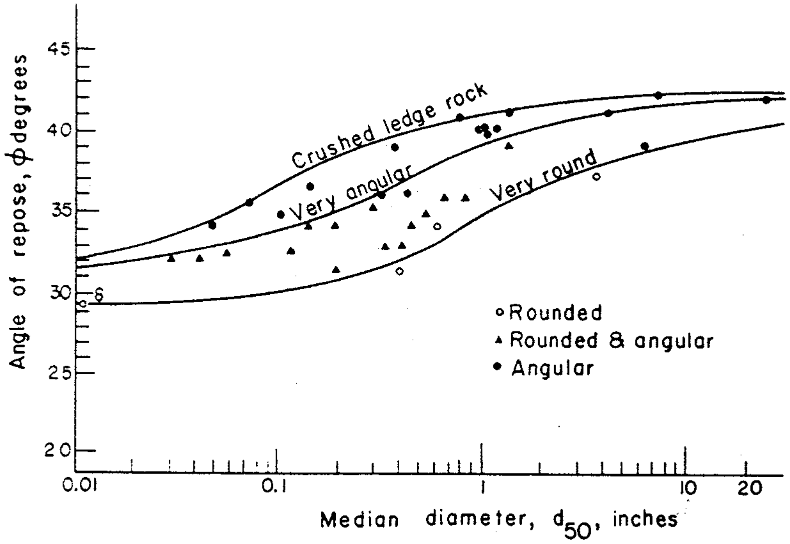


Figure X-3 Angle of Repose for Dumped Riprap (Ref. 45, 48)

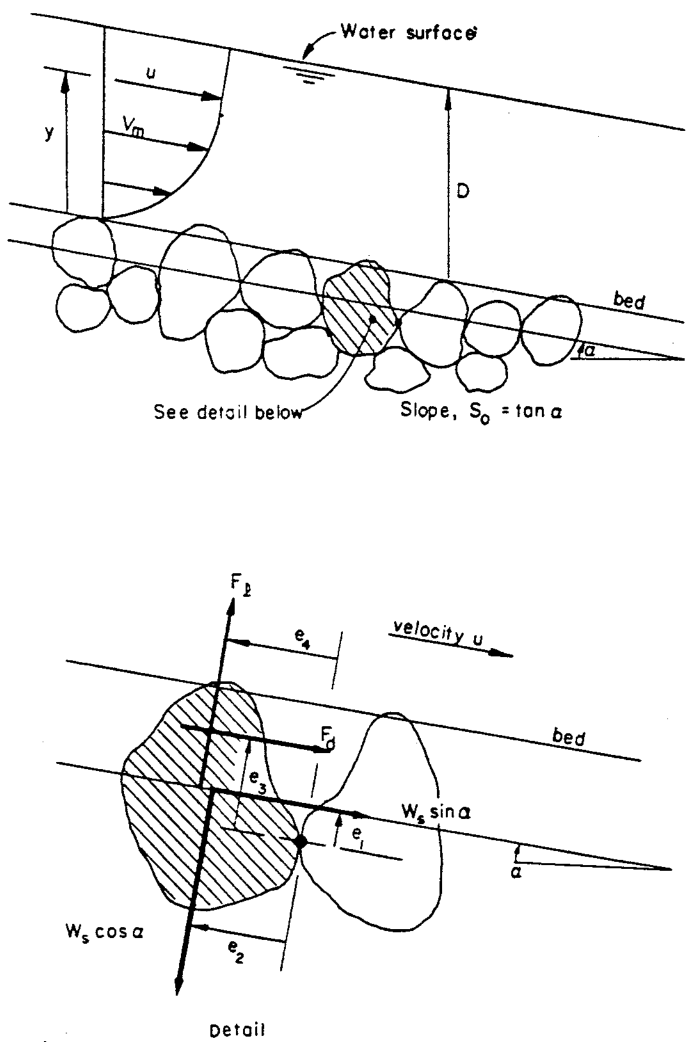


Figure X-4 Definition Sketch For Riprap on Channel Bed (Ref. 45, 48) the ratio of maximum d to d_{50} for large rock. It is usually suggested that the ratio between d_{max} and d_{50} is 2, and between d_{50} and d_{20} is also 2. For the large rock, a ratio of 1.25 between d_{max} and d_{50} is suggested in ref. 51 for steep chutes, because there are concerns regarding the hydraulic and stability effects caused by random boulders. A ratio of 1.5 to 1.6 is therefore recommended as a reasonable ratio because it will allow for stone equivalent to the layer thickness.

Stevens, Simons and Lewis, Safety Factors for Riprap Protection

This paper (ref. 60), which is also presented in more detail in the above reference (ref. 48), formulates an approach to safety factors by considering the position on the bed or bank and the slope. It also considers the relative direction of the flow and the angle of repose of the rock. Although the derivation of the form of the equation considers lift, drag and submerged weight of the particle, Shield's parameter is eventually used as a lumped parameter to consider these forces. The equation is given essentially as:

$$\eta = \frac{21\,\tau}{(S_s-1)\ \gamma d_{50}} = \frac{21\,\tau}{(\gamma_s-\gamma)\ d_{50}} \qquad \text{X.4}$$

where

η = Stability factor

and 21 is the inverse of the Shield's Parameter, given in this document as 0.047. Thus, the investigation for Denver drops uses the equation of this form for various values of Shield's parameter, F_*:

$$\eta = \frac{\tau}{F_*\ (\gamma_s-\gamma)\ d_{50}} \qquad \text{X.5}$$

Stevens derives an equation to consider the safety factor, SF of a particle on sloping bed (see Figure X-4) as:

$$SF = \frac{\cos \alpha \ \tan \phi}{\eta \tan \phi + \sin \alpha} \qquad X.6$$

where

α = angle between the bed and horizontal

ϕ = angle of repose of the rock

The alternative form of this equation is given as:

$$\eta = \cos \alpha (1/SF - \tan \alpha / \tan \phi) \qquad X.7$$

For the investigation of Denver drops, equation X.7 was substituted into X.5, and rearranged to arrive at an equation for d_{50}:

$$d_{50} = \frac{\tau}{F_* (\gamma_s - \gamma) \cos \alpha (1/SF - \tan \alpha / \tan \phi)} \qquad X.8$$

or in terms of depth y and energy grade line slope Se, assuming y can be substituted for R in equation X.1.:

$$d_{50} = \frac{\gamma y \ S_e}{F_* (\gamma_s - \gamma) \cos \alpha (1/SF - \tan \alpha / \tan \phi)} \qquad X.9$$

This equation will be utilized later in analysis of data from Smith and Murray (ref. 52), Bathurst (ref. 4) and Denver case studies.

Stevens presents analysis approaches for banks and other situations, and goes on to examine safety factors inherent in various design approaches (Bureau of Public Roads, COE, California Division of Highways, ASCE Task Committee on Preparation of Sedimentation Manual, Lane and Cambell). This study developes a valuable perspective on these methods.

Maynard, Practical Riprap Design

Maynard completed this investigation (ref. 26) which compared a Froude Number Method to other riprap methods, including bend and bank adjustments. The investigations were oriented toward decelerating flow conditions, for which normal velocity distributions were disrupted, thus making application of shear stress equations difficult (or at least give highly variable results). The equations for various safety factors of incipient motion given are:

$$\frac{d_{50}}{y} = .22\ N_f^3 \qquad \text{for SF} = 1.0 \qquad \text{X.10}$$

$$\frac{d_{50}}{y} = .25\ N_f^3 \qquad \text{for SF} = 1.5 \qquad \text{X.11}$$

$$\frac{d_{50}}{y} = .28\ N_f^3 \qquad \text{for SF} = 2.0 \qquad \text{X.12}$$

where

$$N_f = V/(g\ y)^{\frac{1}{2}} \qquad \text{X.13}$$

The Froude numbers of the model test varied from 0.44 to 0.62, so application for higher Froude numbers is unclear. Since there is a question of the reliability of flow depth predictions in the case of rock drop structures, the related Froude number may be in error and when cubed the error compounds. Thus, while the method appears to have general channel application, it is not proven for the present situation.

REESE, NOMOGRAPHIC RIPRAP DESIGN (ref. 37)

Reese of the COE has completed basic review of this theory (ref. 38) and has compiled an interesting series of design nomographs for channel riprap sizing. They are summarized as follows.

Isbash. This methodology has been applied and developed further by the COE. The form of the equation is:

$$\frac{\rho\ U_b^2}{(\gamma_s - \gamma)\ d_{50}} = 2\ K_I^2 \qquad \text{X.14}$$

where

ρ = mass density

U_b = velocity on the stone, which is commonly taken at mean velocity V

and K_I is a constant, commonly taken as 0.86 for high turbulence, and 1.2 for low turbulence. Interestingly, for the sloping riprap on the drop face, K_I of 1.2 is the correct coefficient to use. This was the coefficient value derived from his model and field data for flow down dumped rock dams. Isbash refers to the coefficient 0.86 in the situation where the rock is dropped on the crest of the dam during placement while water is flowing, where there is little support for the new rock and it is easily moved (ref. 21).

Original Tractive Force Logarithmic Profile. This method fundamentally assumes Shield's parameter and a logarithmic velocity distribution. It is of little value here because the velocity distribution changes rapidly in a drop situation (although it may have application above the crest). It was interesting because they note that Shield's parameter varies from 0.027 to 0.06.

Modified Tractive Force Logarithmic Profile. This is also a similar approach with a slightly different logarithmic velocity profile, it is not appropriate for turbulent flow situations at the drop.

Tractive Force Power Profile. The approach here uses a power function for the velocity distribution, and again, because of the turbulence of the flow down the drop it is not appropriate.

Froude Number Method. This and the Isbash approach, of the 5 Corp's methods, are the more appropriate formulas because the situation at the drop has more of a uniform velocity distribution. This method is the same as previously described by Maynard (ref. 26).

This is a useful reference for design of channel rock riprap. It provides nomographs that consider side slopes, bends, location near hydraulic structures, specific weight, safety factors and other items. They do express concepts which are useful to consider in terms of types of flow. Type I is referred to as having upstream roughness dependance. The concern here, for example, is when a channel with a smoother liner, say concrete or grass, discharges to a riprap surface. At the transition point, the tractive force on the riprap may be greater than after the flow velocity profile has fully developed further downstream on the riprap. The method assumes that the velocity profile of the upstream section may be useful in sizing the riprap. This may apply in the approach section of a drop (and may add light to the problems experienced at the crest of the drops).

Type II is the case where the hydraulics are determined by the riprap roughness. Type III is dependent on boundary geometry, and is the situation at expansion, contractions, sills, drops or other turbulent situations. The Froude and Isbash methods are used for this situation.

Anderson, Paintal and Davenport, Tentative Design Procedure for Riprap - Lined Channels. This reference (ref. 3) and an associated follow-up study (ref. 2) were prepared for the Highway Research Board for design guidance of drainage channels of less than 1000 cfs. It includes a thorough development of allowable shear stress, beginning with a theoretical review of lift and drag. Several important relationships are developed.

First, for roughness, n:

$$n = 0.0395\ d_{50}^{1/6} \qquad \text{X.15}$$

which then can be used in Manning's equation for determination of friction loss or normal flow depth.

Critical boundary shear data of many investigators and two equations are presented. The first is the best fit between the data, and the second is the recommended allowable shear, based on an envelope line of the data.

$$\tau \quad \text{best fit} = 5\ d_{50} \qquad \text{X.16}$$

$$\tau = 4\ d_{50} \qquad \text{X.17}$$

The equivalent Shield's parameters for these equations would be .0486 and .039. Note that the .0486 is essentially the same as the value given by Simons (ref. 48). Obviously then, the second equation provides a degree of safety factor, which was supported by the case studies they followed.

Equation X.16 was developed on data where the relative depth was always more than twice the d_{50} and more commonly greater by a factor of 4. The problem with using any of these values for drop structures is that the relative depth is generally less and thus different conditions exist.

For small channel design at subcritical flow this is a good design reference (ref. 3).

The SCS, in Technical Release No. 59 (ref. 56), has provided guidance through the use of the above equations for sizing riprap gradient control structures. These are basically riprap channels which makes a grade change by flowing at a mild slope (less than 70% of the critical slope). The rock sizing within the channel is conservative, but there have been problems with channel scour downstream (ref. 32). For the magnitude of grade change typically required in the Denver area, these designs are not generally cost effective or practical. It has application to small rundowns and roadside swales.

Samad, Analysis of Riprap for Channel Stabilization.

Dr. Samad (ref. 42) reviews and compiles much of the pertinent data and approaches being utilized. The approach taken in the research examines the stability of a single particle. Deterministic and probabilistic methods are utilized. Data is presented relating the ratio of lift to drag for various Reynolds numbers. Also, coefficient of lift is related to angle of repose, thus taking size and shape into consideration. Determinstic methods are developed which consider the mean dynamic lift pressure as an indirect function of the Shield's relationship.

The probability of adequacy is developed to provide a less subjective evaluation of the safety factor. In other words, we may presently assign a safety factor without understanding what it means in terms of probability. The method has been applied on bank riprap but needs more research to explore the drop application.

A probabilistic method for sizing is also developed which incorporates the random nature of dynamic lift pressure acting on a riprap particle. The potential is then expressed to evaluate the adequacy of riprap through a period of time. This would have been very useful in the economics evaluation later in this investigation.

The method can potentially be applied to sloping rock drops. However, it faces the same limited data base problems (e.g., critical shear stress, pressure-time data) that are encountered for flow down sloping rock drops.

Smith and Murray, Cobble Lined Drop Structures

Smith and Murray (ref. 52) completed flume tests of two dimensional (sides with vertical glass walls), and three dimensional configurations (sides of the same graded rock) of thicknesses of rock layers (1.5 and 2 times the mean diameter); slopes (4, 5, 6 and 7%); and three combinations of rock size and gradation.

The profile utilized included a crest wall which was raised slightly above the upstream channel invert in order to control the upstream drawdown curve. The rock was placed on top of a prepared subgrade which simulated bedding. At the toe of the drop a horizontal bed was used.

The flow for each test was gradually increased until an initial failure was noted. Prior to this initial failure, they note that each incremental increase of flow resulted in dislodging a "few" stones, but that the quantity was insignificant compared to the total volume of rock. The initial failure is described as a sudden dislodging of an area approximately $8d_{50}$ long at the toe of the drop. Nearly simultaneously, movement of all rock upstream to the crest occurred. Reportedly, the rearranged condition was more step like, and comprised of rock mixed with bedding, but many pieces relocated downstream. This same condition was noted by Oliver (ref. 33). This rearranged condition was then stable, reportably because the rock was more interlocked, and flows could be increased until an ultimate failure occurred which resulted in scouring of the subgrade.

The Shield's parameter for the initial failure point as determined by Smith and Murray, it averaged 0.072 (0.068 min.; 0.076 max.) for all tests. They recommended 0.060 in order to provide a safety factor. They also expressed a simple relationship for flow depth, which was at failure point:

$$y = 0.1\ d_{50}/S \qquad \text{X.18}$$

and recommended for design

$$y = 0.116\ d_{50}/S \qquad \text{X.19}$$

where S is the bed slope and y assumes normal depth of flow.

Stevens (ref. 58), applied the findings of Smith and Murray in providing design criteria guidance for the Urban Drainage District. An assumption of normal depth was made, the Shield's parameters from the study were applied, and as stated in the Draft Criteria (ref. 63), no safety factor was applied. The Smith and Murray tests were compiled on slopes of 4, 5, 6 and 7 percent. In reviewing equation X.8, it was clear that the bed slope would inherently result in critical shear being less than if the same velocity and depth parameters were encountered on a flatter slope. As part of this investigation for the Denver drops equation X.9 was applied, with a safety factor of 1, to adjust the Shield's Parameter to a flat slope. The results are given on Table X-1 which illustrates a adjusted Shield's Parameter of 0.0765. The values for all tests are plotted[3] on Figure X-2. The higher values appear reasonable based on the relative depth ratio in Smith and Murray's Model of 1.6 to 2.9 d_{50}, and in accordance with investigations (ref. 65) where relatively larger objects in flow realize a decrease in the drag (lift).

Table X-1
Smith and Murray Data, and Bathurst Data,
Adjustment[3] of Shield's Parameter for Slope

Run No.[1]	Slope	d_{50} (ft.)	Assumed Angle of Repose	_	Shields F* from Raw Data	Shield's F* Adjusted for Slope (MWE)	Reynolds Number
			Smith and Murray's				
1	.04	.05	35	.9421	.0709	.0752	2,085
2	.05	.05	35	.9274	.0679	.0732	2,041
3	.05	.077	37	.9325	.0691	.0741	3,930
4	.06	.077	37	.9187	.0752	.0818	4,103
5	.07	.077	37	.9049	.0709	.0784	3,992
6	.05	.064	39	.9371	.0703	.0750	3,004
7	.07	.064	39	.9113	.0700	.0768	2,993
			Average		.0706	.0764	
			Bathurst				
	.02	.042	37[2]	.9458	.0920	.0973	881
	.05	.042	37[2]	.9325	.1130	.1212	974
	.08	.042	37[2]	.8910	.1700	.1908	1194
	.08	.125	40[2]	.9018	.079	.0876	6198
			Average		.113	.1242	

1 These runs are for the case where the thickness of the rock equalled 1.5 times d_{50}.
2 Assumed by McLaughlin Water Engineers.
3 The "adjusted values" are offered as a qualitative indication of the change in Shield's parameter for bed slope and angle of repose. It is not theoretically proper to plot these "adjusted values" on the Shields diagram because bed slope is considered in its formulation. The plot of the Raw Data values is not significantly different in this case. A different type of relationship would be more appropriate to depict the Shield's parameters as a function of the controlling variables (e.g. relative depth, bed slope, other hydraulic parameters) rather than Reynolds Number.

The Froude No. of the flow upstream of the jump was stated to be less than 2. However, this was determined by calculation rather than physical measurements. Nevertheless, it was observed in the two dimensional models that the transition occurred with "little turbulence" and no well formed jump. The basin length was 6 times the downstream depth and was reported to be sufficiently long.

They note that an extra thickness of rock (3 times the mean rock diameter) is required downstream of the crest so that when movement occurs there is a sufficient supply of stone and support for the crest wall.

In the three dimensional tests, no particular problems were noted on the side slopes through the drop. This was attributed to the fact that the hydraulic shear on the sides was far less than in the middle of the drop, despite the reduced shear resistance on the sides. At the same initial failure flow, the invert failed and the rock was rearranged. This did not occur on the side slopes.

Although the drop structure itself was stable in the three dimensional model, it was noted that problems occurred downstream. These problems included the flow expansion, eddies, and aggradation from the accumulation of displaced riprap. The rock aggradation in the basin deflected flow to "the sides of the discharge channel and resulted in some increased attack on the channel banks beyond the end of the riprap". Specific guidance on the basin length was not given. This of course is troublesome for the District's utilization of this drop.

Another fact that we noted was the apparent uniformity of the material used. One series of tests had a d_{50} of 0.05 ft, the second was 0.077 feet, and the third was a mix of the two with a d_{50} of 0.064 feet. The first two were "relatively uniform because of the narrow range of sieve sizes".

Unfortunately, specific gradation curves are not given. In reviewing typical gradation curves for the District and a picture of sample materials in the reference, it appears that the District's gradation would have a wider range of sizes. Thus, a fraction of the District's rock would be proportionally smaller than the rock in the laboratory test and would have more exposure to movement.

Almost all of the performance characteristics and problems cited in the model study have occurred in various cases described in Section V. These include: stepped rearrangement of the chute through the central portion of the drop; general stability of the side slopes; aggregation of displaced riprap downstream with associated scour and bank erosion downstream; and, failure with complete removal of riprap, particularly at locations just below the crest.

Because of the gradation difference described above, the poor quality of materials provided and placed, and the problems with steeper slopes (described later), the displacement of riprap in Denver is apparently worse than might have been predicted from the paper. In the Surface Mining Water Diversion Design Manual (ref. 51) repeated reference to proper gradation of riprap and bedding layers is emphasized, including the need for proper gradation below the d_{50}. The COE is referenced on disturbances and problems with oversized riprap, or pieces greater than the recommended d_{100} and design thickness. It is clear that without a great deal of care, bedding can be left exposed and smaller pieces of riprap easily dislodged. Techniques to work with large boulders are described later. The reference (ref. 51) recommends that on steeply sloping drops that a relatively small variation from the d_{50} to d_{100} be utilized. The smaller fraction provides good interlocking, filling of voids, and prevents damage to the bedding. The key point is that Smith and Murray used a fairly uniform gradation of rock which seems similar to the recommended gradation in the reference 51.

The fundamental conclusion from qualitative inspection is that the present extent of rock movement observed in the field, or even the amount anticipated by the Smith and Murray "Initial Failure", cannot be tolerated due to its impact on maintenance costs of the drop and due to the potential damage to the downstream channel. It is appropriate to review design safety factors in the parameters, construction specifications, details, design configurations and construction practices that would relieve the problems occurring in the field.

Oliver, Through and Overflow Rockfill Dams (ref. 33)

This study investigates the form of a dumped rock dam and determines the stable slope which the rock takes upon rearrangement. The pnenomena described are similar to that of Isbash (21), and Smith and Murray (ref. 52). A threshold flow is described in terms similar to Smith and Murrays initial failure point. Two key differences in the model are the heavy flow experienced through the rock layers and the downstream transition. Downstream there is sufficient tailwater that the jet stays on the surface and a reverse current pattern exists which helps stabilize the toe.

Oliver regarded the shape and placement of the rock, referring to a packing factor P_c (Unit Area/Number of Stones times the plan area of the average stone). He found that the threshold flow could vary from -40% to +80% depending on the packing factor. This helps to document the need for careful rock gradation and placement.

Oliver argues that the rocks rearrange forming a stepped appearance with horizontal surfaces, and therefore, slope correction similar to that in Equation X.7 is not necessary. It appears that this is not the case from the Denver observations as will be discussed later.

Design curves were given which are similar to the form derived later in this section, but are less conservative. They are derived based on theory, and small model results. Values are shown for unit discharges up to 200 cfs/ft, which are unrealistically high.

<u>References Providing Information on Shields Parameter, Flow Relationships and Roughness for Conditons Similar to District Drop Structures</u>

Wang and Shen, in their paper "Incipient Sediment Motion and Riprap Design" (ref. 65), describe data from China which they used to extend the Shield's diagram to higher Reynolds numbers. This is interesting because such conditions are likely at riprap drop structures. The values are plotted on Figure X-2. They suggest:

$$F_* = .062 \quad \text{for} \quad 100 < R_* < 1 \times 10^5 \qquad X.20$$

and

$$F_* = .25 \quad \text{for } R_* \simeq 10^5 \text{ (or perhaps } > 10^5\text{)} \qquad X.21$$

We noted in their data, relative depths to d_{50} on the order of 10:1 and suspect that this may allow the higher shear stress implied by X.21.

In discussion with Dr. Simons, he notes that investigations conducted for the COE showed an increase in Shield's parameter for laboratory tests of 12-inch stone.

Simons, Li and Associates (ref. 51), provides sizing guidelines for steep channels/drops for small, shallow flows in a mine environment. Clearly, the required rock size is as large or larger than the flow depths. The mechanics of flow are different, with rocks in some areas exposed, while flow cascades around in a highly turbulent, aerated manner. This design technique clearly has application to drainage rundowns, and possibly could be extended to the stacked boulder type of drop. Dr. Simons notes that Bathurst's work (ref. 4), was used in this work.

Bathurst, Hydraulics of Mountain Rivers

Bathurst (ref. 4) has provided valuable research applicable to riprap drop structures. The slope ranges and particle sizes are of the same magnitude of the work by Smith and Murray (ref. 52). Bathurst very thoroughly approaches the analysis of flow resistance and has insight into the entire area of shallow flow relative to roughness elements. His concepts and the investigation herein follow the same philosophies. The formulation for flow is excerpted in Appendix D for those interested in hydralics. The complexities are apparent. His equation is a function of: Froude number; width of flow; d_{50} size relative to the cross stream axis of the rock; the area occupied by rock obstructing the flow (more clearly defined in the Appendix); and, a special function which incorporates the d_{50} size relative to the short axis, width of flow, d_{50} size relative to the cross stream axis, and the standard deviation of the size of rock. These are parameters that are determinable, but for which the effort was beyond the scope of this work. It will be useful in further guidance and research to more accurately estimate flow depths and regimes of flow, and more reliably estimate energy dissipation, which then is related to refined rock sizing.

His data on Shield's parameter is presented in Table X-1 and Figure X-2, after adjustment as part of this investigation for slope. He specifically points out that the Shield's parameter should be adjusted for slope and thus should be higher than the value given.

Other Guidelines Regarding Drop Height, Flow Depth, "Hydraulic Jumps" and Downstream Stability

All of the previous references provide useful information in this regard. Simons (ref. 51) notes that for adequate protection the basin riprap should extend downstream 5 times the tailwater depth. The Smith and Murray discussion of problems with scour below a 3 dimensional trapezoidal basin are of concern. The conclusion arrived at in this investigation is that depression of the basin below the downstream channel invert can be very helpful in dissipating energy and reducing erosion.

Little and Murphy completed a model study of low drop grade control structures (ref. 24, 25) which illustrated the value of the depressed basin, although the practicality and acceptability of the basin depth is questionable for the Metropolitan region. The key guide was when the critical depth was less than the drop height, an undular jump with Froude number less than 1.7 and poor energy dissipation (5%) occurred. Persistance of waves downstream would also result. A specific equation for the boundary between a jump and undular wave conditions was derived from the model as:

$$\frac{y_m}{y_c} = 0.68\left(\frac{H}{y_c}\right)^{-0.19} \qquad \text{X.22}$$

where

y_m = Minimum depth on the face of the drop
y_c = Critical depth
H = Drop height

They note that when H/y_c is greater than 1.2 a direct jump occurs (which is a more practical guideline). They suggest that baffles can be used to help dissipate energy, and suggest a plate configuration with height of approximately Y_c. The baffle pier is referred to as less effective. Design guidelines are given.

In review, it seems that using large boulders on stable foundations could be investigated as an alterntive technique. It is the authors' opinion that the suggested plates and the basin depth are impractical for grass-lined channels in an urban area.

A healthy vegetative cover downstream of the drop basin can be quite helpful in minimizing erosion. SLA (ref. 51), presents work by Parsons in comparing equivalent riprap sizes (Table X-2). In order to provide a healthy vegetative cover, good drainage (typically provided by a stable trickle channel and channel base), construction is necessary.

Table X-2
Equivalent Stone Sizes for Bermuda Grass
Linings (Parsons, 1963) from ref. (51)

Condition of Bermuda Grass	Allowable Shear Stress (lb./sq.ft.)	Allowable Stone Diameter (inches)
Fair stand, short,[1] dormant	0.9	2
Good stand, kept short, dormant	1.1	2
Good stand, long,[2] dormant	2.8	5.5
Excellent stand, kept short, green	2.7	5.5
Good stand, long, green	3.2	6.5

1 Less than 5-inches high.
2 More than 8-inches high.

Linder, Stabilization of Stream Beds with Sheet Piling and Rock Sills

This reference (ref. 23) and the COE (ref. 13) present the background for what has been nick-named herein as the Derrick Stone Approach. This incorporates two concepts.

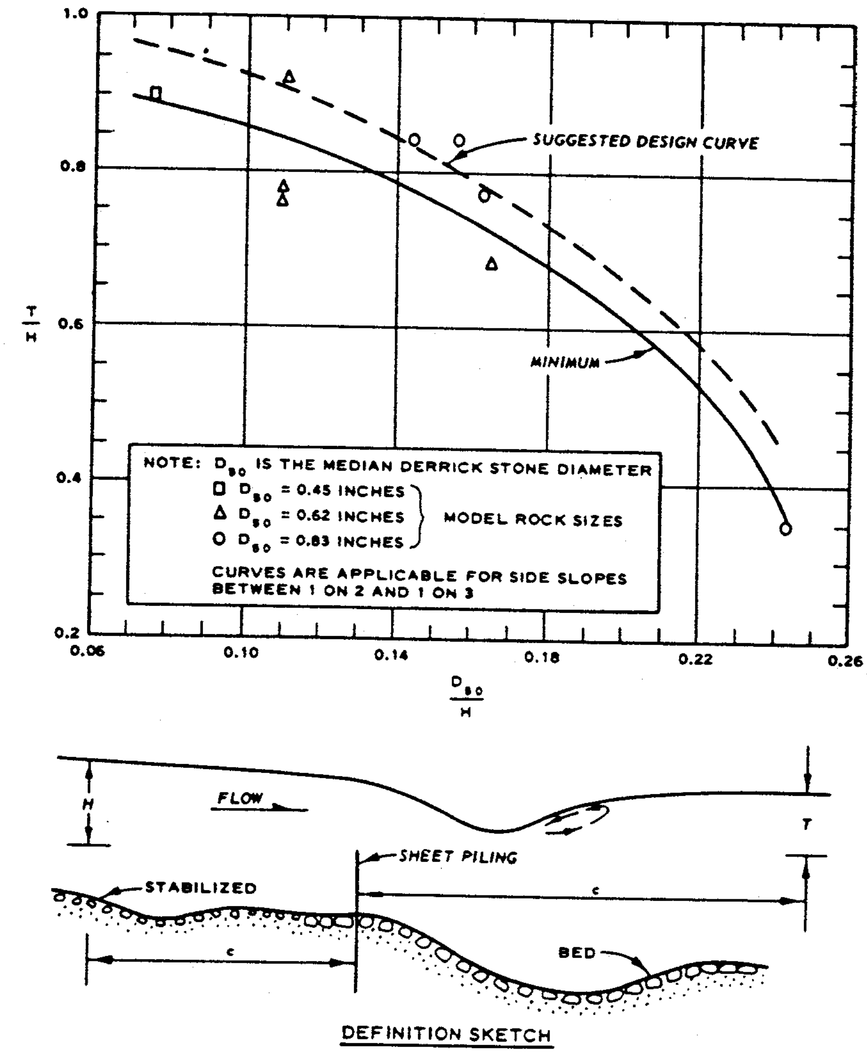
The first, and technically important from a hydraulic perspective, is the case of a drop that is submerged by channel tailwater during design flows. Figures X-5 and X-6 present design guidance and energy loss data. Figure X-7 presents an example design. This work was based on a hydraulic model of structures on the Floyd River, Sioux City, Iowa. In particular, the structures were for an erodible bed channel, but are perceived here to provide guidance for submerged drops. Both references should be consulted for design considerations.

There are several possibilities for scour patterns, both upstream and downstream depending on the tailwater. For the design flow, if the tailwater dropped significantly below critical depth on the crest, scour occurred downstream, which undermined the rock. A fundamental condition is that the high velocity jet over the crest stay on the surface, which was reported to occur if the tailwater elevation was at least 0.8 of the critical depth at the crest.

The second concept is that of the Derrick Stone itself. Instead of a graded riprap, large boulders are placed directly on top of a prepared subgrade, arranged to interlock and minimize voids and displacement of subgrade. Figure V-20 illustrates the concept. The subgrade is typically prepared of at least two layers, a graded riprap and then conventional bedding. All layers are designed to provide a complete reverse filter.

REVIEW OF DISTRICT FIELD CASES

There were several cases where drops had experienced flows for which there was some information in terms of high water marks or flows. The approach used here was to analyze the hydraulics of the particular flow or design flow, and compare the provided rock against various results of various analysis parameters proposed herein.



GRAPH LIMITED TO

$\frac{T}{c} \geq 0.8$

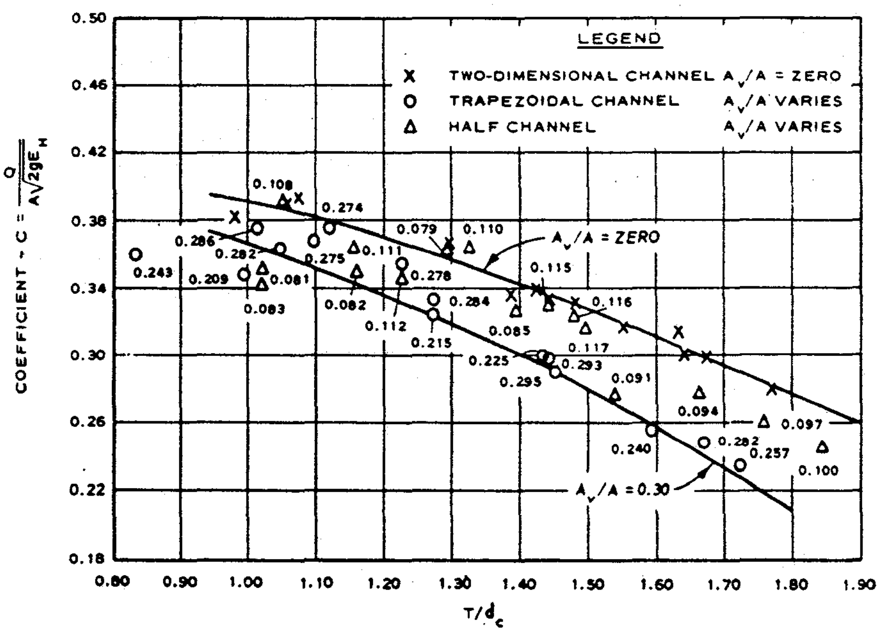
c = CRITICAL DEPTH

SHEET PILING STABILIZER

DERRICK STONE SIZE

Reproduced From EM-1110-2-1601

Figure X-5



NOTE: $E_H = \frac{Q^2}{2A^2C^2g}$

Q = TOTAL DISCHARGE

E_H = ENERGY $\left(\text{TOTAL HEAD, } H + \frac{V^2}{2g}\right)$ ABOVE THE CREST $5d_c$ UPSTREAM OF THE CREST

T = TAILWATER DEPTH ABOVE THE CREST $10d_c$ DOWNSTREAM OF THE CREST

$_c$ = CRITICAL DEPTH FOR THE TRAPEZOIDAL CREST SECTION

CURVE IS APPLICABLE FOR SIDE SLOPES FROM VERTICAL TO 1 ON 3

A = TOTAL AREA ABOVE THE CREST AT $5d_c$ UPSTREAM OF THE CREST

A_v = AREAT IN THE END SECTIONS OF CREST $5d_c$ UPSTREAM OF THE CREST

NUMBERS BESIDE THE PLOTTED POINTS REPRESENT VALUES OF A_v/A

SHEET PILING STABILIZER
ENERGY LOSS

Reproduced From EM-1110-2-1601

Figure X-6

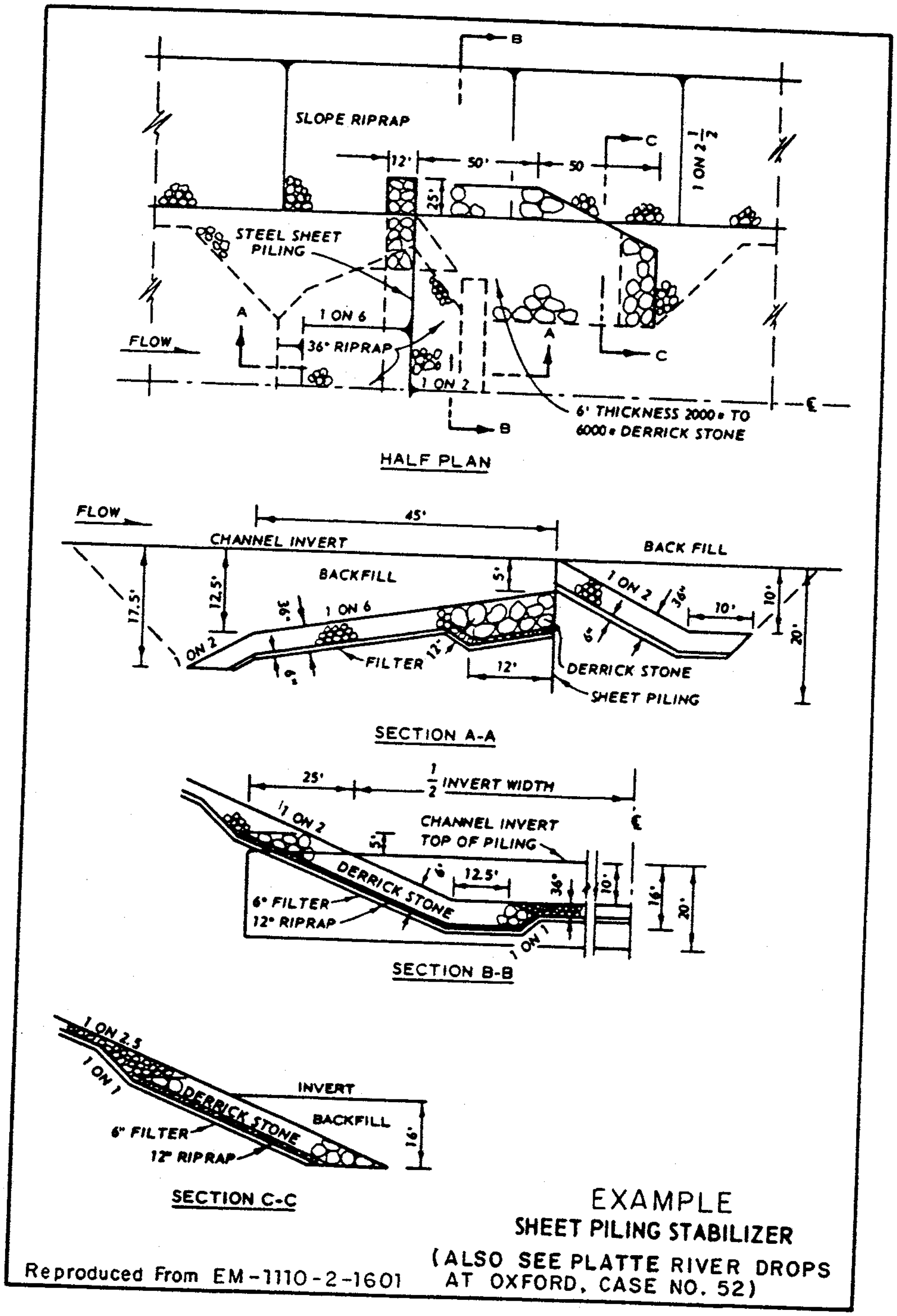

SLOPE RIPRAP
STEEL SHEET PILING
1 ON 6
36" RIPRAP
FLOW
1 ON 2
6' THICKNESS 2000# TO 6000# DERRICK STONE
HALF PLAN
CHANNEL INVERT
BACKFILL
BACK FILL
FILTER
DERRICK STONE
SHEET PILING
SECTION A-A
1/2 INVERT WIDTH
CHANNEL INVERT
TOP OF PILING
DERRICK STONE
6" FILTER
12" RIPRAP
SECTION B-B
1 ON 2.5
1 ON 1
INVERT
BACKFILL
SECTION C-C
EXAMPLE
SHEET PILING STABILIZER
(ALSO SEE PLATTE RIVER DROPS AT OXFORD, CASE NO. 52)
Reproduced From EM-1110-2-1601

Figure X-7

Methodology for Hydraulic Analysis

Many of the approaches used in other studies analyze the required rock size based on hydraulics considering the entire cross-section of flow down the supercritical portion of the drop. It was hypothesized that this was misleading because the typical sideslope areas numerically dampen the true hydraulics within the base width of the drop. Also, since it was becoming apparent that it was beneficial to allow the trickle channel to carry the inherently deeper flow onto the sloping portion of the drop, a methodology was needed to allow for separate analysis.

The flow depth was assumed to be at critical condition for any point along the crest, and accordingly, the critical velocity was a function of the depth at that point.

The basic concept was to use average section hydraulic analysis to determine the elevation of critical flow at the crest. Downstream of the crest, a unit width discharge approach was used where the depth at any given point, particularly below the main discharge crest and along the trickle channel. Figures X-8 and X-9 illustrate the concept. Figure X-8 shows the water surface elevation for critical conditions, Elev. Crit., determined by normal methods for the entire section. The critical depth of flow for the main crest is determined as:

$$y_{cm} = \text{Elev. Crit.} - \text{Elev. Main} \qquad \text{X.23}$$

Flow at the main crest of the drop is assumed to be flowing at critical conditions, thus, the critical velocity (V_{cm}), energy grade line (EGL_m), and unit discharge (q_m) are determined as:

$$V_{cm} = (g\ y_{cm})^{1/2} \qquad \text{X.24}$$

$$EGL_m = y_{cm} + \frac{V_{cm}^2}{2g} + \text{Elev. Main} \qquad \text{X.25}$$

$$q_m = y_{cm}^{3/2}\ g^{1/2} \qquad \text{X.26}$$

where g is the acceleration of gravity.

Similar equations for the trickle channel, with subscript t instead **of m** are:

$$y_{ct} = \text{Elev. Crit.} - \text{Elev. Trickle} \qquad \text{X.27}$$

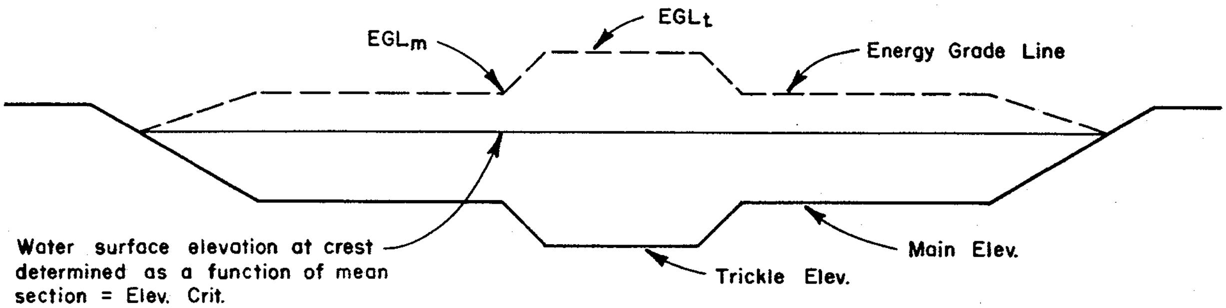
$$V_{ct} = (g\ y_{ct})^{1/2} \qquad \text{X.28}$$

$$EGL_t = y_{ct} + \frac{V_{ct}^2}{2g} + \text{Elev. Trickle} \qquad \text{X.29}$$

$$q_t = y_{ct}^{3/2}\ g^{1/2} \qquad \text{X.30}$$

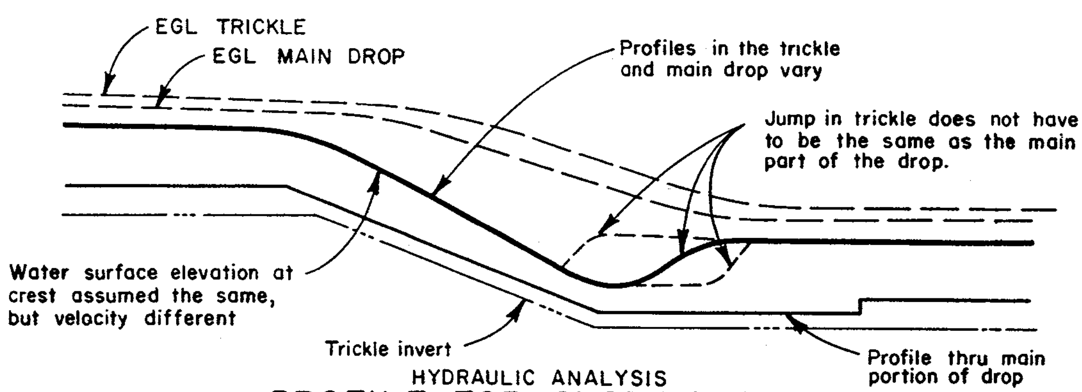
As can be seen in Figure X-8, this results in a reasonably conservative energy gradeline across the section. Figure X-9 illustrates that the water surface profiles downstream can vary until both transitions (the trickle and the main portion of the drop) to subcritical flow have occurred. It also shows the assumption that the point of critical flow occurs at the same point (at the crest). Actually, this is not the case, but the assumption is conservative without having a major impact on rock sizing as will be seen later. In all likelihood, the unit discharge in the trickle is less, but not worth any further analytical effort.

Another improvement in this technique is that it does not automatically assume that the unit discharge in the upstream channel is the same at the crest over the main portion of the drop. We have noted several cases in the field where they vary. It does assume that the discharge in the trickle does not vary down the drop and through the jump. Little flow dispersal is likely through the supercritical portion, but flow expansion is likely through the jump (although not well documented in the literature).



HYDRAULIC ANALYSIS
SECTION AT CREST OF DROP

Figure X-8



HYDRAULIC ANALYSIS
PROFILE FOR SLOPING DROP

Figure X-9

The next step in the effort was to model separate water surface profiles down the face of the drop. A computer program was developed to perform this analysis, determine the location of the jump, and then size the rock based on a variety of different assumptions.

The determination of the jump was accomplished through the comparison of specific force, F above and below the drop, using the following general equation (add subscript t or m for trickle or main channel).

$$F = \frac{q^2}{g\,y} + \frac{y^2}{2} \qquad \text{X.31}$$

Note that on low drops the jump may occur on the face of the drop and one should refer to references (10, 34) for drops on sloping faces. This was found to have some effect on rock sizing, but it was generally small. In the case of total submergence, one should also refer to the submerged drop analysis by the Corps described previously (ref. 13, 23). We have noted several cases where the hydraulics are different for various frequencies and thus require both types of analysis. For example, the Lee Gulch Dam during the 10-year flood cascades down the drop and forms a jump, but is completely submerged during the 100-year flood.

Methodology for Rock Sizing Analysis

The approach used in the Draft Criteria was to assume normal depth of flow. It was determined as part of the analysis herein that this would give much larger rock size for lower drops than appropriate. Also, it gave misleading results when trying to determine Shield's Parameter. Therefore, flow depths and conditions based on a water surface profile analysis were used.

Originally in this investigation, uncorrected Shield's parameters from Smith and Murray (ref. 52), were used without making any special correction for slope, in order to compare failure or incipient motion that had been observed in District drops. Actually, this analysis compared favorably with the observations in the field, but there was concern as to the lack of direct input of actual drop slopes relative to the angle of repose of the stone, and the shift in Reynolds number from the magnitude of 24×10^3 to 24×10^5 (or higher).

Therefore, the correction for drop slope, holding the safety factor to 1.0, was input per equation X.9. Various Shield's parameters were input, with the approach being to find the best value that gave d_{50} values that agreed with conditions of incipient motion in terms of the d_{50} observed in the field; or, in the case of failures or proven stability for a given flow predicted a stable d_{50} that was greater than or less than the observed d_{50} respectively. Four values of F_* were used:

0.0767	Which was the Smith and Murray data corrected to a flat slope
0.0909	Trial value close to a good fit[1]
0.1000	Trial value close to a good fit
0.2500	Value suggested by Shen (ref. 65)

1 The odd value comes from a simplified form of equation X.9, $d_{50} = 6.666\ y\ S_e/\eta$

Figure X-10 illustrates the predicted d_{50} values based on the above Shield's parameters relative to the observed d_{50} (denoted as "PROVIDED"). Also, a size is given based on a safety factor of 1.5 and a Shield's parameter of 0.10. Figure X-11 is a similar comparison utilizing Shield's parameters of 0.10 and 0.0909, both having safety factors of 1.5. Also, quite interestingly, a plot of d_{50} based on Isbash's equation (see equation X.14) is presented. It appears that the descriptions of flow over sloping rock dams were close to the situation here, and as Isbash had both laboratory and field data, it seemed reasonable to temper the choice of parameters.

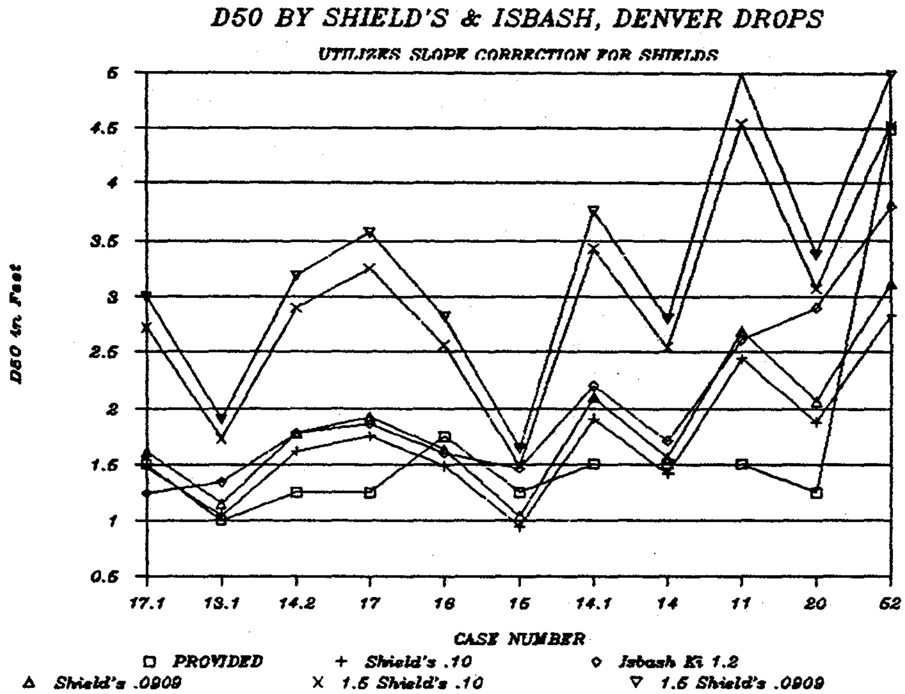


Figure X-10

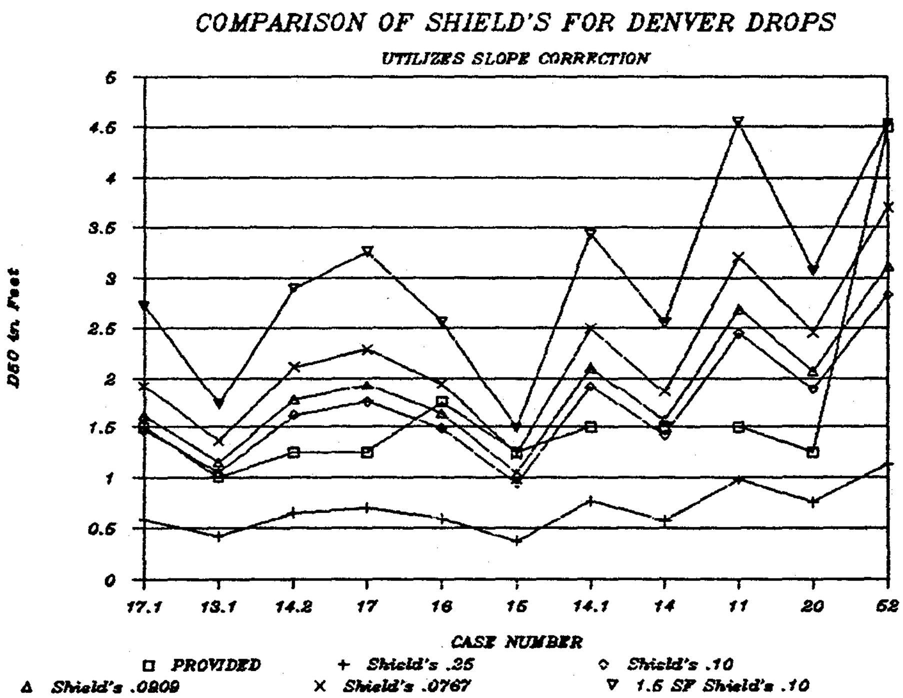


Figure X-11

Table X-3 summarizes the key analysis. The conclusions here are: 1) that a value of 0.25 is too high; 2) the 0.0767 value is probably appropriate for smaller Reynolds numbers; 3) it appears that the value of .091 matches the data from Isbash and is a conservative judgement when considering the safety factor; and, 4) the slope correction from Stevens is a prudent step. Figures X-12 and -13 compare the Shield's parameter of 0.091 and the slope correction with the case of the Isbash equation only. They illustrate that the effect of steep slope requires larger rock than Isbash's equation, and smaller rock for flatter slopes. The rough equivalency point appears to be near a six to one slope. The safety factor, also effected by the slope correction, is a reasonable approach that should result in structures with little movement. Clearly, utilization of this approach will lead to flatter slopes when utilizing District graded riprap. Alternatively, the "Derrick" stone type of placement can allow for greater rock size (and less relative thickness), as indicated in Figure V-20.

DESIGN GUIDANCE

The present Draft Criteria should be revised and upgraded. It would appear reasonable to consider other drop options entirely and dissuade usage of this type of drop, especially without careful evaluation of all the parameters involved, and acknowledgement by the owner of the risks and problems involved.

Improvement in the design should include incorporation of a trickle channel through the crest and the drop. Separate hydraulic analysis should be made for the main drop and the trickle channel including determination of unit discharge, water surface profile analysis, and jump analysis.

The determination of appropriate rock size should consider the location in the main drop or the trickle channel, utilize a Shield's parameter of 0.091, and a safety factor of 1.5 using equation X.9. A conservative value for angle of repose should be used. All the following graphs herein have used 42°.

Table X-3
Evaluation of Denver Sloping Drop
Cases to Determine Appropriate Shield's Parameters

Case	Location	Total cfs	q cfs/ft.	Slope	Comments	Conclusions	Best F*
17.1	Bear Canyon Creek Drop 5	320	11.16	4:1	Only a few rocks moved in this event.	Either .10 or .0909 ok, but .0909 would indicate only smaller rocks would move.	.0909
13.1	Cherry Creek	1,000	16.04	7:1	The 12-inch stone provided had little movement at 400 cfs, but we suspect would have much more movement at 1,000.	Isbash value inclined us to go with .0909 or smaller.	<.0909
14.2	Liberty Hill, Tributary Georgetown Village	400	21.10	4.5:1	There was significant rock movement during this event and scour downstream.	Either .10 or .0909 ok, as would predict failure, inclined to go with value near Isbash.	.0909
17	Bear Canyon Creek Drop 9	600	22.43	4:1	Massive failure during event.	Either .10 or .0909 ok, as would predict failure, inclined to go with value near Isbash.	.0909
16	Little Dry Creek, Westminster	2,640	25.18	5.35:1	Smaller rock was moved, there are many oversized boulders (poorly placed), generally stable.	Appears reasonable to go with .0909, but this is not a strong case.	.0909
15	Lone Tree	1,300	29.48	11.5:1	One of the best drops, only slight amount of movement below trickle that daylights of crest. Basically stable, note that Isbash calls for larger rock.	The .0767 intersects with size in field, but basically stable.	.0767-.0909
14 14.1	Little Dry Creek Georgetown	660	32.48	4.5:1	The same case, except 14.1 estimates effect of culvert backwater submergence of drop. Some movement noted, but not a failure like 14.2.	.0909 shields and Isbash indicates some movement.	.0909
11	Massey Draw	2,085	32.38	4:1	Rock is moving	Hard to tell because rock clearly undersized.	.0909
20	Tributary to Englewood Dam	965	47.15	8:1	Rock moving badly and jump washout indicated.	Note, Isbash indicates lower value.	.0767 - .0909
52	South Platte River at Oxford	16,400	116.5	10:1	Analyzed as conventional jump for comparison. Indicates conservative design.	N/A	N/A

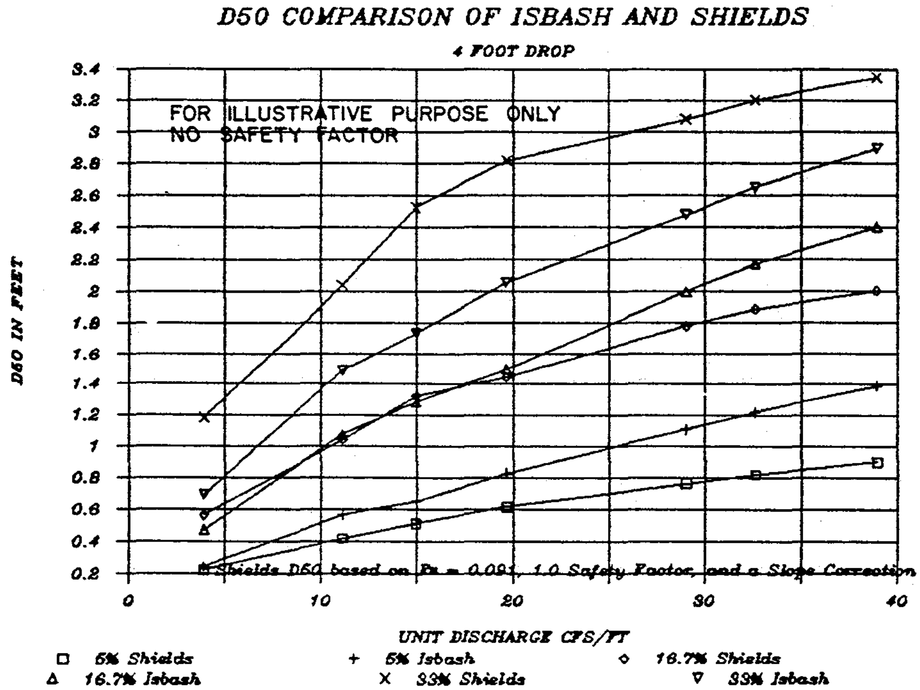


Figure X-12

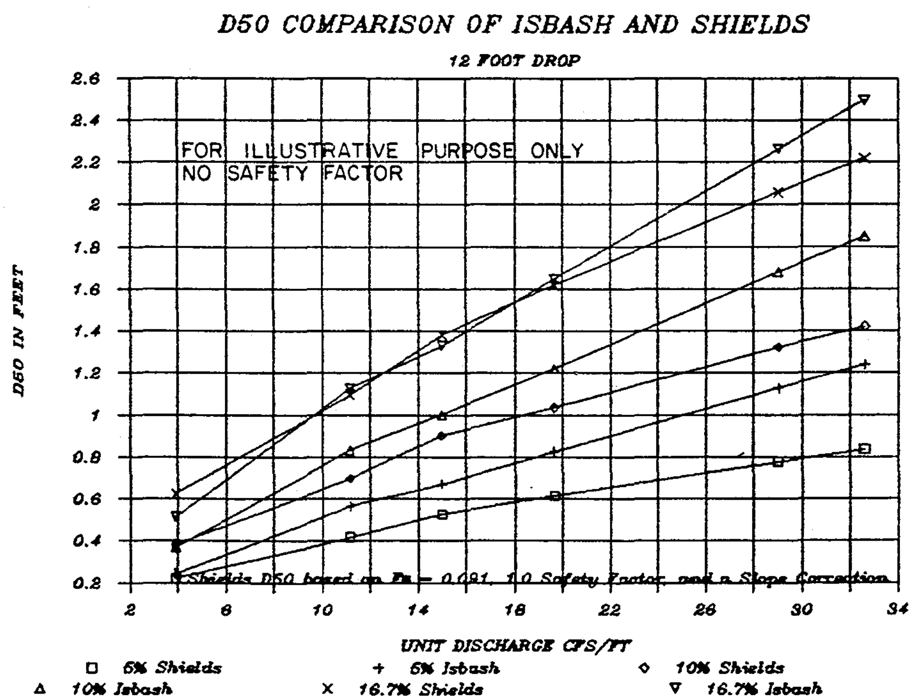


Figure X-13

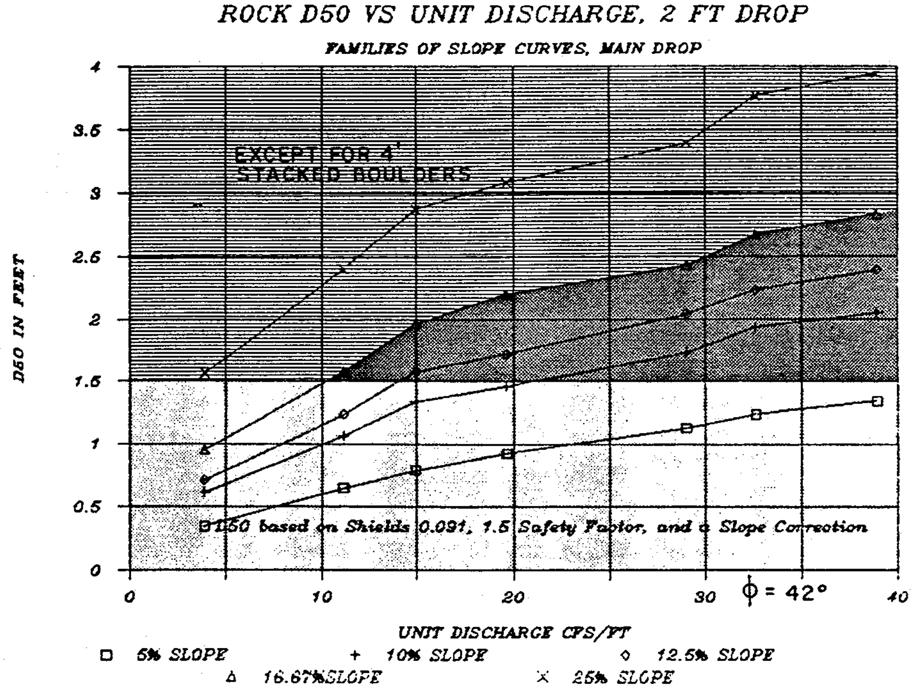
Froude number and the relative drop height to critical depth ratio should be checked. The trickle channel downstream should be utilized to create a depressed stilling basin for the main jump. Normally, a 1.5 to 2 foot deep trickle is recommended, which allows depression of the main basin approximately 1 foot (with a shallower trickle channel through the basin).

The trickle channel will create the need for an increase in rock size and the basin length in the trickle area. As a rule of thumb, we recommend that the width of heavier trickle rock be 3 times the width of the trickle channel. Also, we would recommend using large boulders which obstruct the flow of the trickle in the basin, and if necessary, in the main basin to reduce downstream erosion. Extra care in adjacent rock placement and foundations for the large rock will be required. This same recommendation is made for several types of drops, thus, the District and design engineers are advised to monitor progress and problems so that design guidelines can be refined.

Figures X-14 to X-15 are design guideline curves which are based on 200 hypothetical (including Figures X-16 and X-17) case studies on the previously mentioned computer program. Pairs of curves are given for the main drop and the adjoining trickle channel, and generally assume a trickle depth of 2 feet (except 1 foot is assumed for q_m<5cfs/ft and 1.5 foot for q_m<12 cfs/foot). The analysis has included several slopes and drop heights.

The depths of the main stilling basins should be 1/2 or more the trickle and are generally 1 foot for q_m>15 cfs/ft. Slopes should be kept flatter than 6:1 and generally flatter than 8:1. Because of the trigonometic functions involved with increasing slope, the slightest change makes a significant difference in rock size when using steeper slopes. There is some possibility for stacked large boulder drops, where the rock approaches the drop height. These are experimental at this point and should only be done with the concurrance of the District and the client.

The jump length for the main basin and the trickle channel should be calculated, including the usual case in the trickle channel where supercritical flow will usually extend downstream before the jump begins.



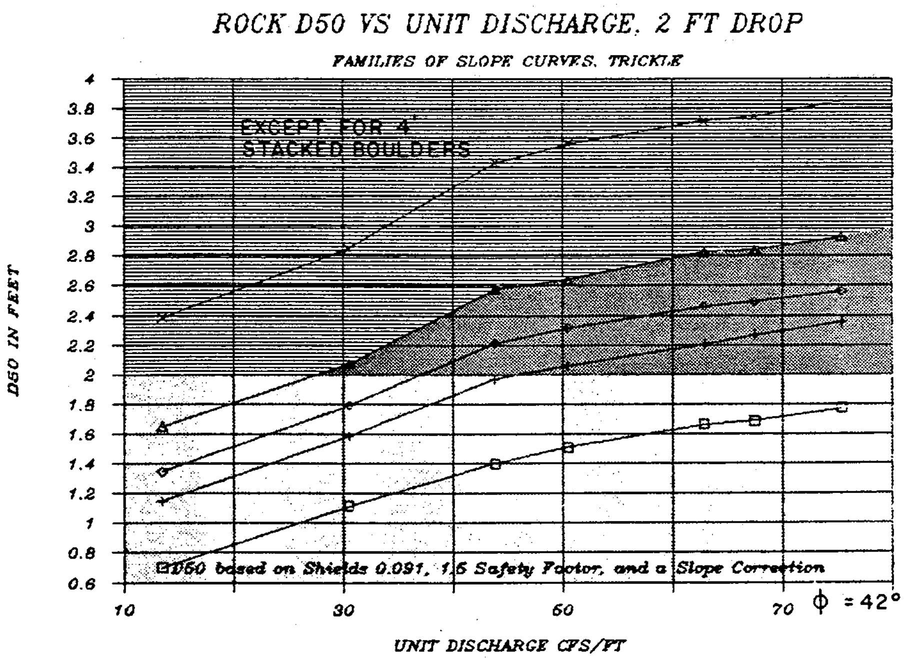
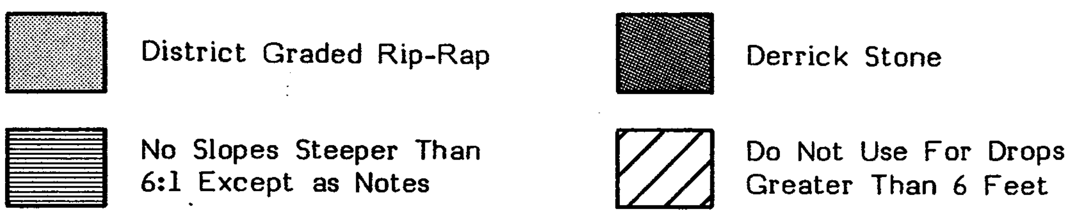
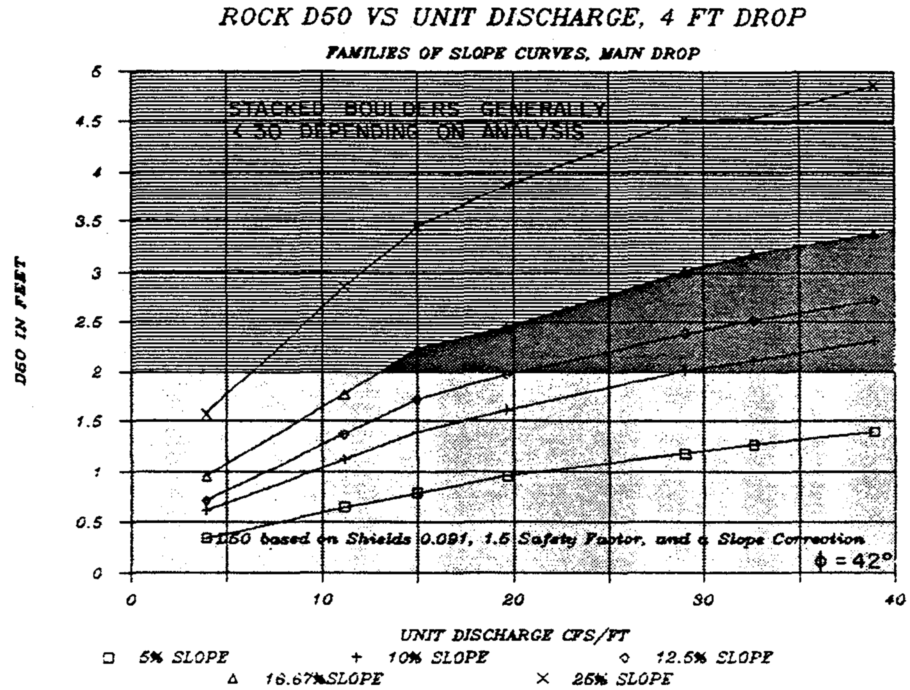


Figure X-14

Design Guideline Curve 2 Ft. Drops





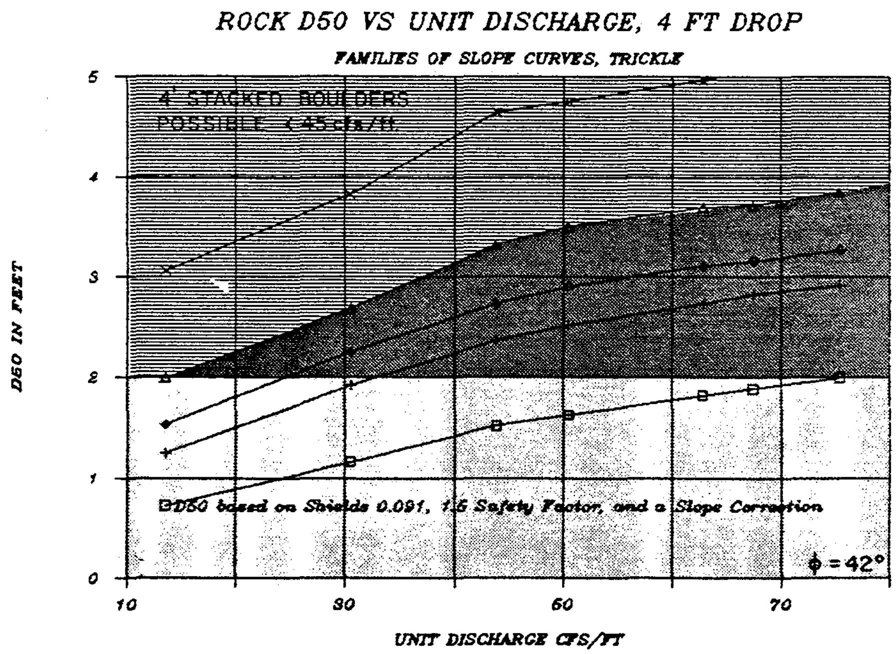


Figure X-15

Design Guideline Curve 4 Ft. Drops

District Graded Rip-Rap	Derrick Stone
No Slopes Steeper Than 6:1 Except as Notes	Do Not Use For Drops Greater Than 6 Feet

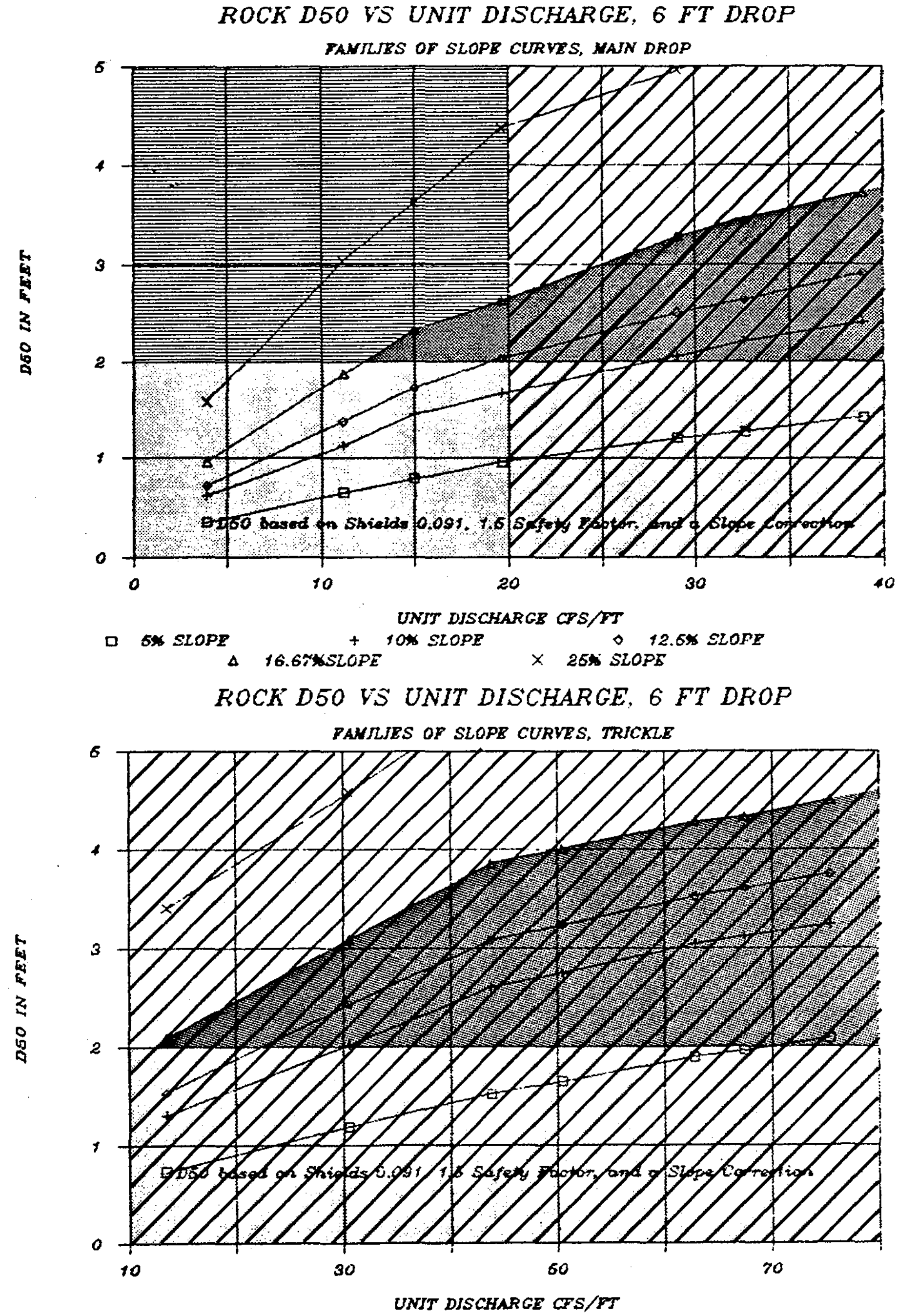
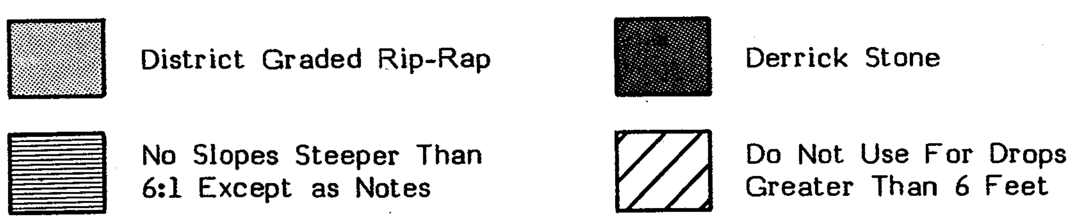


Figure X-16

Information Curve and Guideline for Q<500

and Interpolation Between 4 and 6 Foot Drop



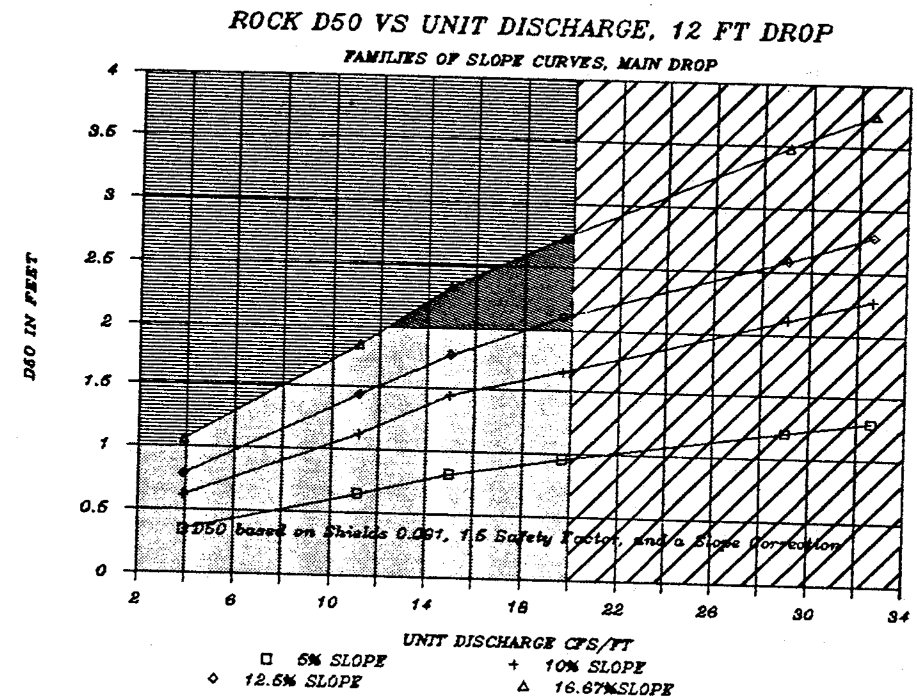


Figure X-17

Information Curve and Guideline for Rundowns Q<500

District Graded Rip-Rap

Derrick Stone

No Slopes Steeper Than 6:1 Except as Notes

Do Not Use For Drops Greater Than 6 Feet

The analysis has assumed an angle of repose for the stone of 42 degrees. This should be reviewed for each design, and specified within a reasonable range.

Figures X-16 and X-17 are presented, largely to allow for guidance in designing rundowns (channels to carry tributary flows into main channel) for flows less than about 500 cfs. Also Figure X-16 can be used when drops are between 4 foot and 6 foot. Normally, drops greater than 4 feet should be avoided. In the situation where a design channel, say of 4 foot nominal depth, had to fall 6 foot total, it would be preferable for energy dissipation and reduction of downstream erosion to have one drop rather than 4 foot and 2 foot drops.

Much improvement is needed in details, specifications, and quality control; including gradation tests, materials, and placement. The concept of dumped riprap is totally misleading. Realizing that all the relationships indicate that the smaller size fraction will wash away, it is imperative that the d_{50} and larger material be placed so that it is exposed and flush with the surface. The interstices should be filled with rock that is not likely to be displaced and is as large as possible, and/or securely wedged between the larger pieces in a mixture of smaller material. The remaining riprap should act as a reverse filter and a leveling course.

Alternative riprap placement techniques may be feasible, but the owner should be responsible for maintaining the structure for a period of time until the majority of rock movement and weak spots have been identified.

SECTION XI

GROUTED ROCK REVIEW

INTRODUCTION

As discussed previously, seepage uplift is the key force controlling the stability of grouted riprap. Net uplift forces vary as a function of location, cutoff measures, drain gallery locations and water surface profile through the basin.

The 200 cases analyzed in Section X provided an opportunity to analyze the uplift and surface hydraulic forces of grouted rock drops.

FORCES

Figure XI-1 illustrates the forces involved. Five basic points were analyzed. Point 1 was approximately 5 feet downstream of the toe, and was selected as the location downstream of the point where the deflection (turning) force of the surface flow had occurred. Point 2, was at the toe where the turning force was encountered.

Point 3 varied in location to reflect alternative drain locations. When a drain was used that was perpendicular to the drop face, Point 3 was located 25% of the distance up the sloping portion of the drop. When a horizontal drain was used, Point 3 was moved to a location perpendicular to the sloping surface that intercepted the toe of the drop. Point 4 was 50% of the distance up the drop slope. Point 5 was the point underneath the grout layer at the intersection of the subgrade under the crest and the top of the drop.

It turned out that Point 3 was usually the critical pressure location, regardless of the drain orientation. In some cases, Point 1 had a low safety factor because of shallow supercritical flow.

Weight of Water

The weight of water is a function of the depth of flow. Thus, the greater the roughness, the greater the weight.

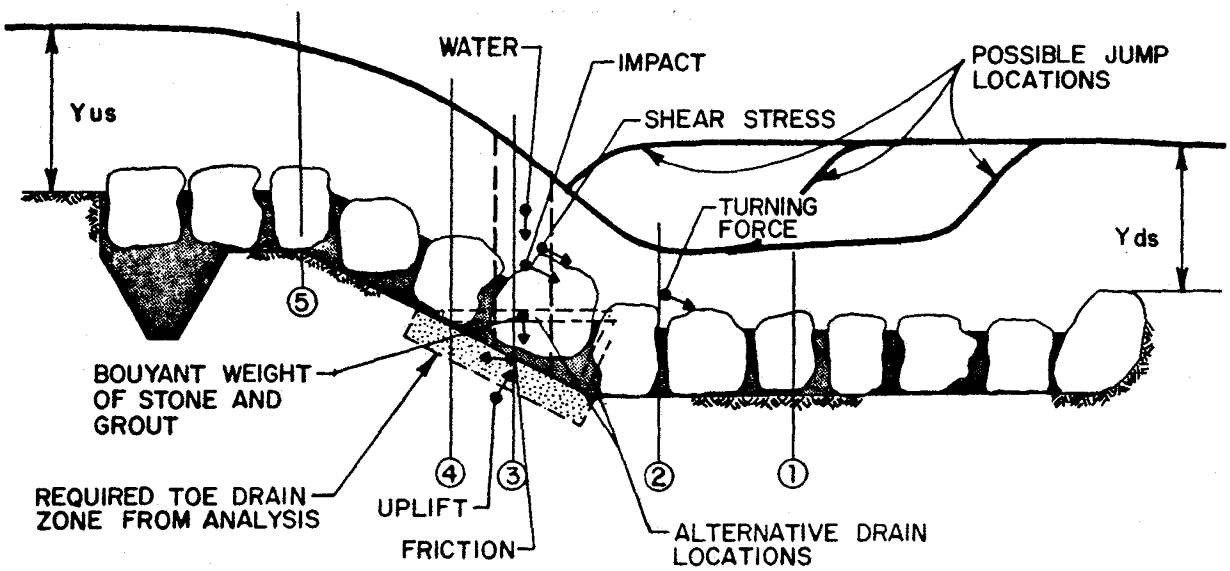


Figure XI-1

Grouted Rock Force Schematic

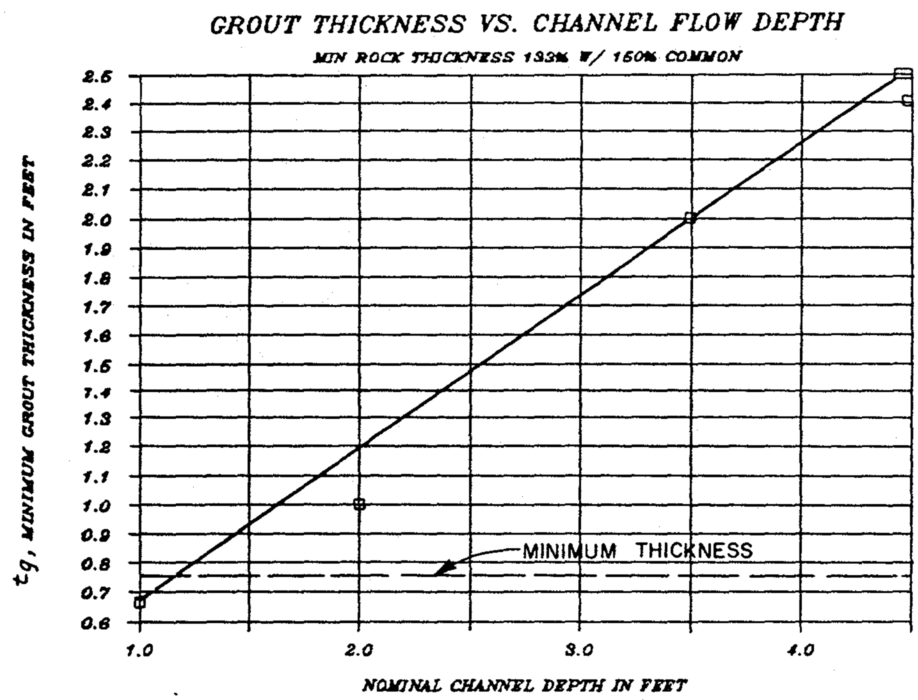


Figure XI-2

Design Guideline for Grout Thickness

Shear Stress

Equation X.1 is transformed for unit width and the actual water surface profile.

$$\tau_u = y\ S_e \qquad \text{XI.1}$$

Bouyant Weight of Rock and Grout

The rock was assumed to project up above the grout layer a maximum of 50 percent of the grout thickness. On the average, the rock is assumed to protrude half of the grout depth, therefore, the bouyant weight is assumed to be a function of 1.25 times the grout thickness.

Impact Force

The water flowing down the drop will directly impact any abrupt rock faces. The assumption made above allows the rock to project 25% of the grout thickness, t_g. An impact coefficient, C_i, of 0.333 was assumed in Equation XI.2 for the impact force.

$$F_i = C_i \quad \frac{V^2}{2} \ (.25\ t_g) \qquad \text{XI.2}$$

Uplift Pressure

Lanes weighted creep (see Equation XII.1 in the following section), was used to prorate the pressure differential from upstream normal channel depth or downstream normal channel depth, relative to the water head over the toe drain (the water level of the surface flow over the drain). Thus, it can be seen by examining Figure XI-1 that there can be troublesome pressure differentials from either upstream or downstream when there is shallow supercritical flow. As noted in reference 50, one may consider a downstream cutoff. It is also possible to have other weep locations, as long as the proper creep ratio is provided. This is particularly true for flatter slopes.

Turning Force

At Point 2, a turning force impacts the basin as a function of slope change. Basically, this was a positive force countering uplift and causing no great stress in the grouted rock.

Friction

With net vertical weight, it was assumed that there would be a horizontal force resisting motion. A coefficient of 0.5 was used, and multiplied by the net weight to determine the friction force.

Frost Heave

This value was not computed, but should be considered. The general thicknesses of grout recommended herein should not be significantly affected, but this should be monitored.

ANALYSIS

All of the above forces were resolved into vertical and horizontal components. The horizontal components were small and capable of being resisted by the strength of the grout and rock (generally less than 1 psi). When problems occurred in various trials, they were generally a result of net vertical instability at Point 3. If a horizontal drain was used, the location under the sloping face perpendicular to the toe would be unstable, while other locations had a Safety Factor generally greater than 1.3. If a perpendicular drain to the toe was provided, Point 3 would be unstable, while other locations generally had a safety factor greater than 1.3.

Conclusion

It was concluded that a large toe drain was generally needed as shown. With the toe drain provided, the analysis illustrated that the design would be stable (safety factor $\geq$ 1.3) with the flow depth vs. grout thickness relationship shown in Figure XI-2.

Figure XI-2 can be used as a design guideline for grout thickness. The rock should nominally be 150% of the grout thickness, with the minimum being 133% of the grout thickness. This recommendation assumes a specific gravity of 2.65, thus curves would have to be developed, or forces checked for lesser specific gravity. This analysis was performed assuming a contiguous trickle channel and it was found that the same recommended thicknesses were adequate. The depth to enter the table with respect to the main channel, is the nominal channel depth (not critical) upstream of the crest (basically the flow depth in the channel upstream of the cutoff and above the drawdown curve).

The critical design factor is seepage cutoff. It is readily seen that underflow could easily lift a major slab of rock and grout; depending upon the exposure, the surface flow could cause further undermining or displacement. If seepage is not cutoff such that the uplift pressure exceeds those determined by Lanes Weighted Creep Method, then this relationship is not valid.

Regarding slope, the main problem was with regard to hydraulics. Generally, 4 to 1 or flatter should be used. Steeper structures are feasible but require more analysis.

SECTION XII
DESIGN GUIDELINES

INTRODUCTION

Design guidelines are discussed in this section to assist the engineer in addressing critical design factors. They are based upon the evaluation of the drops inspected in the field and serve to highlight improvement recommendations.

Five major categories are described to present design guideline recommendations and illustrate typical structural characteristics.

TYPES OF DROPS

The first structure type considered is the vertical riprap drop (VRR), which was originally presented by the UDFCD, 1982 (ref. 63), and Stevens (ref. 58). It is slightly modified here to include a trickle channel. The second and third designs are an improved sloping large, riprap drop (SLR) and a grouted sloping boulder drop (GSB). The rock size, grout layer depth and basin configurations for these two types of structures are based on rock sizing criteria described previously, combined with water surface profile and weighted creep computations for seepage. The fourth type is the USBR Baffle (Apron) Chute (BC). The fifth structure category is a vertical face hard basin (VHB), which is a composite design based on several existing structures. Considering only these five drop structure types is not meant to be an exhaustive comparison, or in any way prohibit other possible designs. The intent is to provide a framework for evaluation which includes these principle design categories. Many material substitutions, proposed alternatives, design modifications, or a combination of designs may be viewed in context of the design guidelines presented herein.

General Procedure

The design procedures presented herein are generalized. The designer should use these guidelines to identify the most suitable approach, with the understanding that detailed analytical methods and design specifications may vary as a function of site conditions and hydraulic performance. A standard drop structure design approach would include at least the following steps:

1) Define the maximum design discharge (usually the 100-year) and other discharges appropriate for analysis (e.g. trickle flows, 2 year or other discharge expected to occur on a more frequent bais).

2) Select possible drop structure alternatives to be considered (Sections XIII and XIV provide guidance).

3) Establish the channel hydraulic parameters, reviewing drop and channel combinations that may be the most effective.

4) Determine the required longitudinal channels slope and the total drop height required to produce the desired hydraulic conditions.

5) Apply separate hydraulic analyses to the main channel drop and the trickle flow zones to determine the extent of protection required, as well as, the potential problems/solutions for each. This approach is discussed in Section X (Refer to Figures X-8 and X-9, and related text).

6) Perform soils and seepage analyses to obtain structural design information.

7) Use specific design criteria to determine the drop structure dimensions, material requirements and construction methods.

Drop Selection

The selection of the type of drop structure is flexible and may include: land uses, cost, aesthetics, maintenance or other considerations. A primary concern should be achieving functional hydraulic performance.

Any grass-lined channel or sandy channel will establish some kind of equilibrium (or at least a range) over time. The point of drop structures is to establish grade changes such that excessive degradation and aggradation does not occur. Therefore, the design of the drops should begin only after an assessment of what constitutes stable grades for existing natural channels, and/or after an assessment of improved channel options. There are also trade offs between drops and channel lining options which allow for steeper gradients.

Planning must include provisions for other site grading problems and concerns. It is often desirable to incorporate drainageways and drop structures into open space and park planning. There are numerous references on these matters (3, 11, 13, 18, 19, 23, 31, 32, 47, 48, 49, 50, 51, 53, 54, 55, 56, 66).

Crest Approach Analysis

With control at the drop crest, upstream water surface profile computations are used to estimate the distance that protection should be maintained upstream; that is, the distance to where localized velocities have acceptable values. Backwater computations also yield the maximum upstream flow depth which is necessary to size wall abutment and bank heights.

As part of this analysis the critical water surface elevation at the crest will be determined. This elevation is important to the following steps.

The higher shear stress created by smoother linings should be taken into consideration when sizing riprap. One can look at any of several approaches, but Reese (37) presents nomographs that may be more readily used.

Water Surface Profile Analysis for Drop Structures

Separate water surface profile computations should be performed using the trickle and main channel unit discharges from the crest of the drop through the hydraulic jump (see Section X).

Supercritical water surface profile computations should be performed to predict the location of the hydraulic jump. This information is critical to determine the required length of the basins necessary to contain the jump. It should be apparent that higher trickle channel flows will most likely require extended protection in the trickle zone, which should be integrated into the structure design.

The designers should stay abreast of research and practical results of designs which use this approach. In the case of rock and grouted rock basins, the key concept is to use the rougher surfaces to dissipate residual energy, and in many cases, large boulders may be used as baffles to dissipate the stronger jet in the trickle channel and adjacent area. The entire subject of jumps in trapezoidal sections is subject to further development (ref. 30, 44, 52). For a given discharge there is a balance between the crest base width, upstream and downstream flow velocities, and the Froude number in the drop basin. These parameters may be optimized for specific applications; however, crest width constrictions generally result in unreasonable basin length requirements.

Water surface profile may be accomplished by the "Standard Step Method" (Chow, ref. 10), or any equivalent method suitable for unit discharge computations. This investigation found for reliable profile analysis down the face of the drop that it took 4 to 5 increments, with 2 smaller increments at the crest. An example of a jump location computation sheet is shown in Table XII-1. The standard step method was adapted to spreadsheet software and additional columns were formulated for specific force (F) per equation X.31, and Froude number (N_F) computations for each increment. The Froude number is useful for considering the type of jump which may be expected. When the Froude number is less than 1.7, an undular jump is likely to form which can persist downstream and produce localized, high velocity erosion problems. See Equation X.22 and references (24, 25). Design configurations should be optimized to avoid this potential condition.

The best estimate of the desired basin length is between 3.6 and 6 times the tailwater depth, with 5 to 6 being the most advisable, and longer with erosive soils depending on the nature of the jump.

Seepage Analysis and Control

A variety of seepage evaluations may be applied. The most common technique is that proposed by E.W. Lane, 1935, (ref. 67) commonly referred to as "Lane's Weighted Creep Method". The essential elements of this method are paraphrased (ref. 7) as follows:

Backwater Calculation by Standard Step Method
Vertical Drop in Rectangular Channel
Distance to Hydraulic Jump

Q=	1500	So=	0.003	h=	13.0	Specific Force F	
Hd=	12.0	n=	0.02	D=	0.02		
b2=	45	alpha=	1.1	Y1=	1.20	F1=	29.44
qc=	33.33333	Yc=	3.25	Y2=Yn+1=	5.48	F2=	21.31

trial Z	dx	Sum dx	Y	A	R	V	Hv
1.201	0.00	0.0	1.20	54.06	1.14	27.747	13.150
1.289	10.00	10.0	1.26	56.65	1.19	26.478	11.975
1.377	10.00	20.0	1.32	59.24	1.24	25.320	10.950
1.464	10.00	30.0	1.37	61.84	1.30	24.257	10.051
1.552	10.00	40.0	1.43	64.44	1.35	23.277	9.255
1.640	10.00	50.0	1.49	67.06	1.40	22.369	8.547
1.729	10.00	60.0	1.55	69.69	1.45	21.523	7.913
1.818	10.00	70.0	1.61	72.36	1.50	20.730	7.340
1.908	10.00	80.0	1.67	75.06	1.55	19.985	6.822
1.999	10.00	90.0	1.73	77.80	1.61	19.281	6.350
2.091	10.00	100.0	1.79	80.57	1.66	18.617	5.920
2.184	10.00	110.0	1.85	83.41	1.71	17.983	5.524
2.277	10.00	120.0	1.92	86.25	1.77	17.391	5.166
2.370	10.00	130.0	1.98	89.09	1.82	16.837	4.842
2.463	10.00	140.0	2.04	91.93	1.87	16.317	4.547
2.556	10.00	150.0	2.11	94.77	1.93	15.828	4.279

Sf	mean Sf	hf	H est	H act	E	F1	Nf
0.117063		0.000	14.351	14.351	14.35	29.44	4.46
0.100485	0.108774	1.088	13.264	13.264	13.23	28.20	4.16
0.086849	0.093667	0.937	12.327	12.327	12.27	27.08	3.89
0.075534	0.081191	0.812	11.515	11.515	11.42	26.06	3.65
0.066050	0.070792	0.708	10.807	10.807	10.69	25.12	3.43
0.058033	0.062041	0.620	10.187	10.187	10.04	24.27	3.23
0.051205	0.054619	0.546	9.641	9.641	9.46	23.48	3.05
0.045328	0.048267	0.483	9.158	9.158	8.95	22.75	2.88
0.040260	0.042794	0.428	8.730	8.730	8.49	22.08	2.73
0.035846	0.038053	0.381	8.349	8.349	8.08	21.45	2.58
0.032001	0.033923	0.339	8.010	8.010	7.71	20.87	2.45
0.028612	0.030306	0.303	7.707	7.707	7.38	20.33	2.33
0.025680	0.027146	0.271	7.443	7.436	7.08	19.84	2.21
0.023133	0.024406	0.244	7.212	7.192	6.82	19.39	2.11
0.020908	0.022020	0.220	7.010	6.971	6.59	18.98	2.01
0.018957	0.019933	0.199	6.835	6.772	6.39	18.60	1.92

Table XII-1

Backwater Calculation by Standard Step Method

Vertical Drop in Rectangular Channel

Distance to Hydraulic Jump

(1) The weighted-creep distance of a cross-section of a dam is the sum of the vertical creep distances (along contact surfaces steeper than 45°), L_V, plus one-third of the horizontal creep distances (along contact surfaces less than 45°), L_H.

(2) The weighted-creep head ratio is defined as:

$$C_W = \frac{L_H + 3\ L_V}{3H} \qquad \text{XII.I}$$

where

C_W = weighted creep ratio

The values in Table XII-2 should not be exceeded.

(3) Reverse filter drains, weep holes, and pipe drains are aids to security from under seepage, and recommended safe weighted-creep head ratios may be reduced as much as 10 percent if they are used.

(4) Care must be exercised to insure that cutoffs are properly tied in at the ends so that the water will not outflank them.

(5) The upward pressure to be used in design may be estimated by assuming that the drop in pressure from headwater to tailwater along the contact line of the dam and foundation is proportional to the weighted-creep distance.

Table XII-2

Lane's Weighted Creep: Recommended Ratios

Material	Ratio
Very fine sand or silt	8.5
Fine sand	7.0
Medium sand	6.0
Coarse sand	5.0
Fine gravel	4.0
Medium gravel	3.5
Coarse gravel including cobbles	3.0
Boulders with some cobbles and gravel	2.5
Soft clay	3.0
Medium clay	2.0
Hard clay	1.8
Very hard clay or hardpan	1.6

An applied example of this technique can be found in the USBR "Design of Small Dams" (ref. 7), on pages 341-342. Seepage considerations should be included in the design of cutoff walls, wall footings, drains, filters, structural slabs, and grouted masses.

Seepage is controlled by increasing the seepage length such that C_W is lowered to a conservative value. Soils tests must be taken during design and confirmed during construction. These tests are especially critical for reinforced concrete and grout structures.

They are also important for sloping riprap, as the crest is the last line of defense when rock movement occurs. Locating cutoffs upstream of the crest and using horizontal impervious blankets can be effective. It is also very important to control lateral seepage around the structure. (H should be calculated as the elevation of the crest minus the elevation of the bedding subgrade just downstream of the crest.)

Common Variables

The following guidelines have several common variables. In the direction of flow, the longitudinal profiles for all drops share a few common features. Each has an approach length (L_a), a crest or cutoff wall which varies in height (Hc_w) depending on the drop height (H_d), and other factors. A face length (L_f), either vertical or sloping at ratio (z_f), a basin length (L_b) which may be level with the channel downstream or depressed as noted, and an amount (B) relative to the downstream channel invert. In the cross-section, there is a channel base width (b), trapezoidal side slope (z_s), channel depth of normal depth (y_n) plus one foot freeboard, and the corresponding top width (T at y_n+1). Channel lining in the drop section is either concrete, rock of depth (D_r) placed on a bedding layer (D_b), or grouted boulders with a grout depth (D_g). With these common characteristics established, the particular design features may be identified.

VRR - VERTICAL RIPRAP DROP: UDFCD CRITERION, 1982 (SEE FIGURE XII-1)

a. There is no base width constriction in the drop. The apron length is determined by using backwater water surface profile calculations.

b. The crestwall is a structural retaining wall which is buried at least 3 feet below the level of the rock bedding layer in the drop basin. A trickle channel is carried through the wall. The top of the crest wall should not extend above the upstream invert elevation. The trickle slab should be tied to the structure and consider wall movement.

c. Crestwall and footer dimensions are determined by conventional structural methods. Underdrain requirements are determined from seepage analysis.

d. Flow energy is dispersed in the loose rock basin which is depressed below the downstream invert elevation.

e. There is a transition length downstream of the basin to gradually bring the basin level to that of the channel downstream.

f. Separate analysis of rock sizing and basin depression should be made for the main drop and the trickle.

g. A contingency factor of 25% to 50% should be applied to the rock depth in areas of erosive soils since experience has shown that basin rock rearrangement can cause collapse into the basin center.

h. With the preceding amendments, the basin length, depression depth, transition length, and rock sizing are defined. The following discussion is adapted from ref. (58) by Stevens who prepared the guidance document used by the Urban Drainage District in "Design Criteria for Riprap Drop Structures" ref. (63). The design is essentially that which was developed and model tested by C.D. Smith. The structure is an adaption of the reinforced concrete vertical drop structure to smaller heads and drop heights.

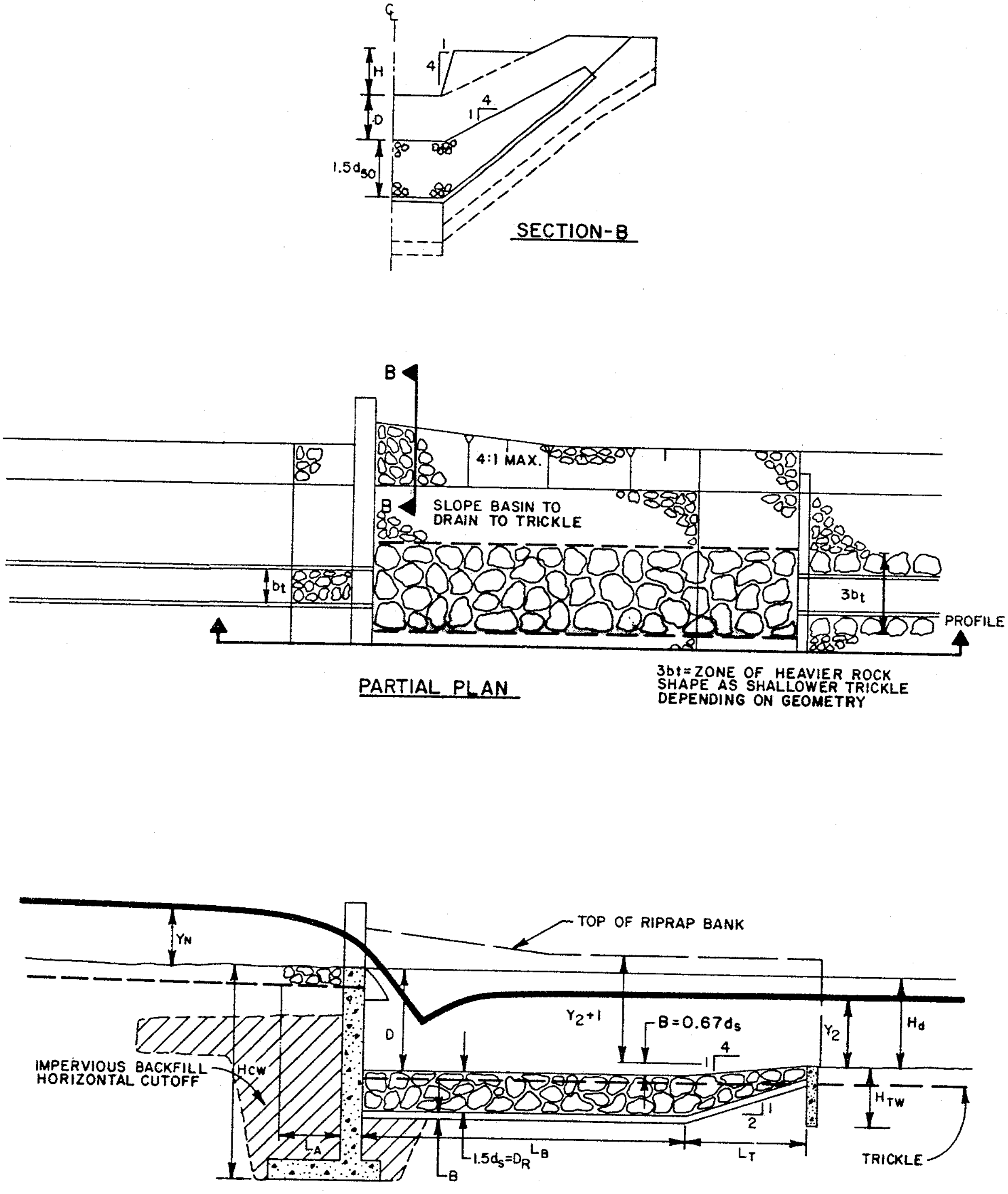


Figure XII-1
VRR - Vertical Riprap Drop

The head on the crest is the level of the energy gradeline above the crest of the drop. The crest wall height above the main channel is given by the equation:

$$H_m = EGL_m - \text{Elev. Main at the main crest} \qquad \text{XII.1}$$

where the EGL_m is defined by Equation X.25.

The wingwalls (Figure XII-1) are required to direct the flow coming along the sides of the approach channel into the plunge pool. The width of the crest is the same as the bed of the approach section. The height of the wingwalls above the main crest is:

$$h = H_m \qquad \text{XII.2}$$

where Elev. Main is the elevation of the main crest.

The wingwalls must extend below the depth of excavation for the plunge pool and must provide an adequately long seepage path to prevent piping. Separate analysis at the trickle channel is required.

where

$$H_t = EGL_t - \text{Elev. Trickle} \qquad \text{XII.3}$$

EGL_t is defined by Equation X.29.

The plunge pool is a deep bed of rock riprap initially placed level across the floor of plunge pool and extending downstream.

$$L_b = 4H + 0.25D \qquad \text{XII.4}$$

The first flow over the weir falls on initially flat rock bed and begins to form a scour hole. The rocks removed from the scour hole are deposited in the area between the scour hole and the beginning of the downstream channel. With substantial flow or a repetition of flow, a mound of stones forms downstream from the scour hole. The mound is an integral part of the energy dissipating structure and must be maintained. This is achieved by initially placing the top of the stone bed below the downstream channel bed, by an amount equal to two-thirds of the scour depth d_s at the design discharge. The scour hole must be allowed to develop by natural means and generally should not be performed.

The desired drop across the structure is the difference in the bed elevations of the approach channel at the weir and the downstream channel at the end of the structure. Let this difference be H_d. It follows from Figure XII-1 that

$$H_d = D - 0.67d_s \quad \text{XII.5}$$

The designer must find the combination of rock size and jet plunge height D that gives a depth of scour which balances Equation XII.5. The relation between rock size d_m, jet plunge height height D, head on the weir H and depth of scour d_s is given in Figure XII-2. As these values will be different in the main drop and the trickle, the design d_{50} and/or d_s will vary. This assumes that this is an appropriate extrapolation of the modeling work, which would appear reasonable if the trickle and adjacent areas are treated conservatively.

To obtain an adequate cutoff, the depth of the vertical wall that forms the weir crest must extend below the bottom of the excavation for the riprap. Therefore, Smith's view is that it is usually uneconomical to design a scour depth d_s any greater than 0.3D. To meet this limitation in the field it is necessary to: increase the rock size d_{50}; decrease the jet plunge height D (by using more drops); decrease H (by using a wider structure); or, to use another type of drop structure.

The side slopes in the basin must be riprapped also as there are strong back currents in the basin. A sand and gravel or cloth filter is required under this riprap. The side slopes in the basin should be the same slope as for the downstream channel (but no steeper than 4 horizontal to 1 vertical per District guidelines).

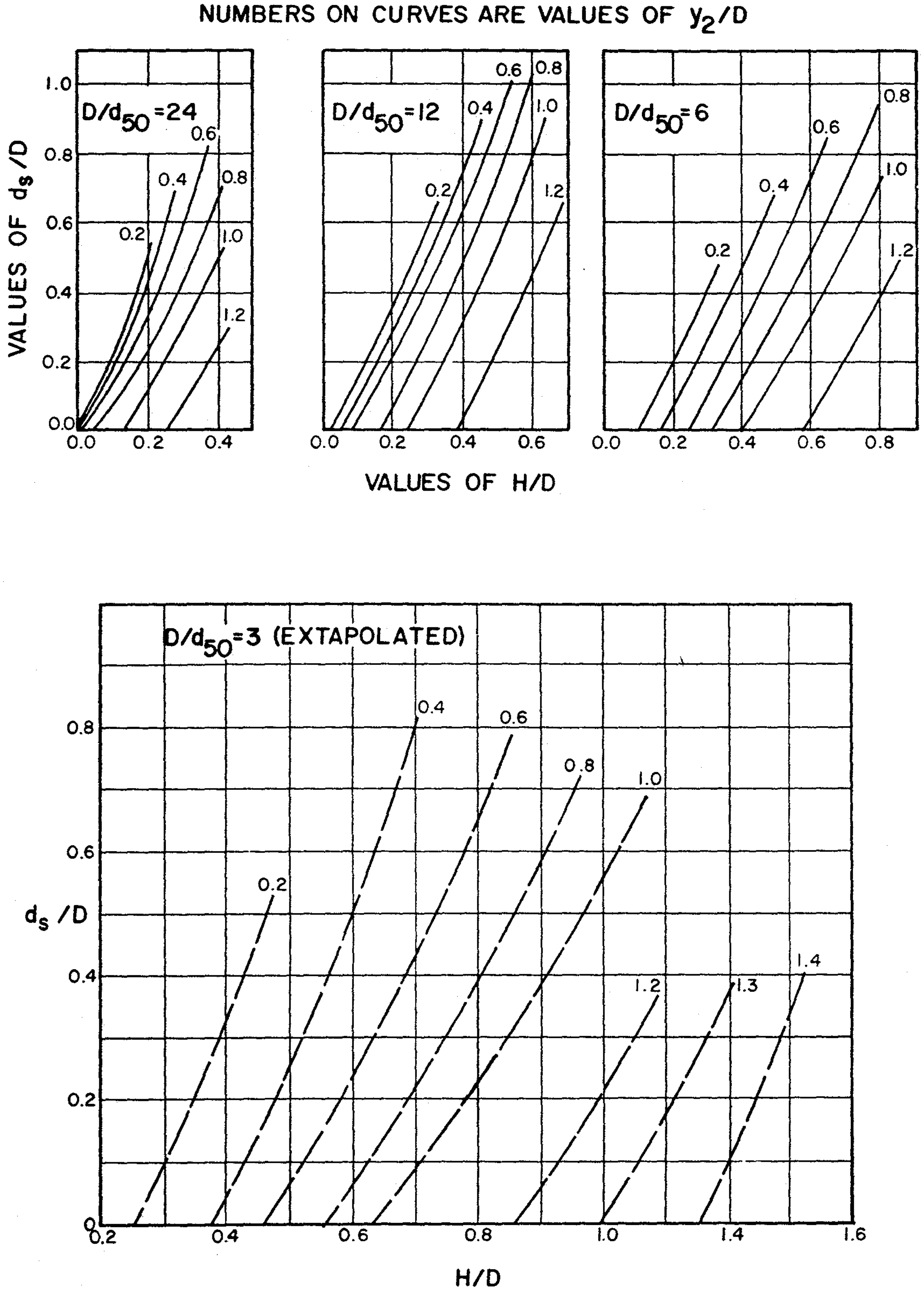


Figure XII-2

Curves for Scour Depth at Vertical Drop

SLR - SLOPING LARGE RIPRAP DROP PER SECTION X (SEE FIGURE III-3)

a. Determine trial layout and rock sizing; see Figures X-14, X-15, and X-16 for guideline values.

b. According to Section X determine unit discharge in trickle channel and on main crest.

c. Compute water surface profile analysis on the face of the drop and in basin below (see Figures X-8 and X-9). Compute separately the main drop and the drop through the trickle channel using Manning's n according to Equation X.15. Use the roughness value to compute friction loss in hydraulic analysis. Do not assume normal depth (practically requires computer program).

d. Determine the location of the hydraulic jump. If tailwater is greater than the crest elevation, consider COE approach (ref. 13, 23; see Figures X-5, X-6, X-7). Normally, the controlling velocity, depth and energy grade line slope parameters reflect conditions at the toe of drop. The jump is usually located at the toe or on the face of the main drop. The trickle flow travels downstream in the basin before the jump occurs. From the point where the jump is initiated, it appears that a length of 5 to 6 times the tailwater depth is appropriate. This should be reviewed for each case.

e. Using Equation X.9, iterate the acceptable solution for d_{50} based on verification of reasonable assumptions for trial d_{50}, and the angle of repose of riprap (see Figure X-3).

f. Guideline values may be determined from Figures X-14, X-15, and X-16 but they are based upon: the angle of repose equal to 42°; other assumptions for trickle depths (2 foot in the channel, 1 foot in basin); and basin depression (1 foot) as described in Section X. If required d_{50}'s are different than the original assumptions, the entire process has to be repeated until they are equal.

g. Use of the guideline values in Figures X-14, X-15, X-16 and X-17 should be tempered with the following:

i) Slopes flatter than six to one are inherently much safer. In Equation X.9, the safety factor is adjusted by a trignometric function which rapidly increases the required sizing and shows more sensitivity to errors in slope.

ii) The maximum graded riprap specified by the District has a d_{50} of 2 feet. Basically, use of this riprap will involve flatter slopes.

iii) If conditions arise where steeper slopes or larger d_{50} are required, the Derrick stone placement approach has merit. But this will involve special placement of large boulders to match surfaces and minimize voids. Place well graded riprap in the remaining voids so that it is interlocked and cannot be moved. The stacked boulder approach is similar and viable. The key guideline is to have each boulder step such that the upstream boulder is half way below the top of the downstream boulder and the voids are filled with material that is not easily displaced.

iv) Figure X-16 is provided for the case where a 4 to 6 foot drop is unavoidable.

v) Figures X-16 and X-17 provide guidance on discharges less than 500 cfs for drainage swales, rundowns, etc. The designer is also referred to ref. 51 for similar steep channels.

vi) One can shift from the main drop family of curves to the trickle channel family of curves (subject to the condition of the same trickle/basin depths). The flows given at each location are in pairs, thus, if one calculates the main drop unit discharge, the trickle unit discharge can be interpolated based on the proportion that the value is between adjoining values on the main drop curves.

h. Evaluate the stability of the jump below the main drop and through trickle channel. If further depression of the basin is not feasible, consider using large boulders that protrude into the flow (ideally as much as 0.6 to 0.8 y_c as in BC drops, but this may be difficult to achieve), and creating a couple of bends in the trickle in order to dissipate energy.

i. Boulders in horizontal basins can be evaluated based on the velocity just upstream of the jump and by using the Isbash Equation (X.14). Normally, K_t is taken as 1.2, but should be assumed to be 0.86 because of high turbulence and reduced interlocking. All adjoining rock should be large with care taken to fill all voids with interlocking riprap and provide a subgrade comprised of riprap and bedding (the effects of this initial recommendation should be monitored). Alternatively, smaller boulders may be considered with the provision of utilizing grout to interlock the rock to subgrade in these high turbulence areas. (Do not leave the grout high as the intent is to have roughness, and it would not be aesthetic.)

The heavier rock at the trickle channel should extend laterally so that there is a width of heavier rock equal to 3 times the base width b_t of the trickle channel. This is an estimate of what might be needed to stabilize the rock against the diverging/converging flow conditions. Stacked boulders, stepped in a ledge like fashion in the trickle and carefully arranged (and placed with adequate riprap to fill voids and provide subgrade), is a recommended approach.

j. Absolute minimum thickness of riprap is 1.5 d_{50}, with 2.0 d_{50} at the crest (see Figure XIII-3). Generally, the height of the rock on the banks should be critical depth for the main drop y_{cm} plus 1 foot.

k. Very conservative bedding should be implemented. At minimum use 12-inches of material that is tightly matched to the riprap above it. The quarry gradation test of the riprap should be matched with an actual gradation test for the bedding, and the bedding with the subgrade. Other approaches may eventually prove superior, such as complete gradations within the riprap provided, but this was not observed in this literature review.

l. The crest approach should be devised as described in the introductory remarks. There is no contraction or sill (it only aggrades anyway), and the upstream protection L_A can be longer (e.g. 15 to 25 feet).

m. Improved specifications should be utilized and enforced. A sample of a draft specification is provided in Appendix B. Provisions should be made for adjustments and repairs to the rock work, especially in cases where there are jump problems.

n. The owner should be appraised of the potential problems, especially that the forces involved are random and that localized pressure fluctuations can suddenly dislodge rock. Movement is inevitable, but is dramatically accelerated and magnified in quantity by weakness in analysis, design, material, construction and inspection.

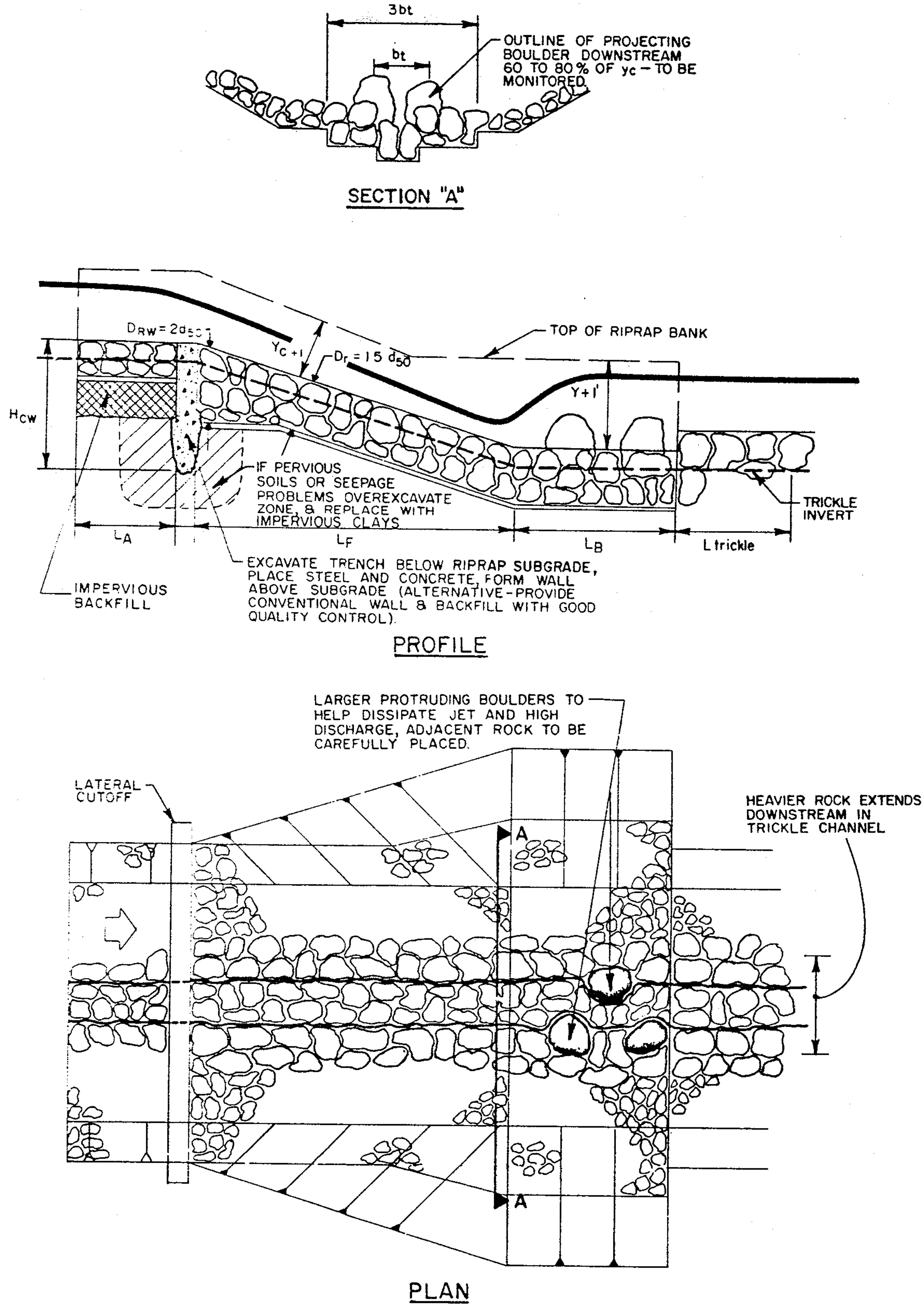


Figure XII-3

SLR - Sloping Large Riprap Drop

GSB - GROUTED SLOPING BOULDER DROP (SEE FIGURE XII-4)

a. The upstream apron has 8-10 foot length of grouted boulders and must cover the area from the crest upstream and over the cutoff. Further distance may be required to control the drawdown velocities.

b. The vertical cutoff is located upstream of the crest a minimum of 5 feet. Locating the cutoff further upstream is helpful to seepage control. Analysis of specific site soils and evalution of seepage is critical. The vertical cutoff can be constructed by excavating a "clean" trench and backfilling with concrete, sheetpile, or concrete slurry walls. Other techniques include: overexcavation of a zone and replacement with compacted impervious clay with or without cutoff walls; concrete cutoff walls with clay backfill taking great care to compact along the wall surface; and impervious liners in a trapezoidal trench filled with clay.

c. The trickle channel continues through the entire drop section, typically 1 foot deep, except at the transitions back to the grass-lined channel and the crest where it is 2 foot. The trickle channel protection extends past the main channel protection as determined by the separate hydraulic analysis. In the depressed basin, larger boulders and trickle channel meanders can be used to dissipate the jet and associated energy.

d. Grout thickness t_g, is determined based upon a minimum safety factor of 1.3 (see Section XI). Figure XI-2 presents a guideline curve.

e. The rock generally considered are large boulders (d > 2 ft.) which are carefully placed to create stepwise drop and trickle sections. The rock size in all directions is $1.33t_g$ minimum, with many pieces being 1.5 t_g (see Section XI).

f. The main stilling basin is depressed, typically a foot, in order to stabilize the jump. An analysis of the jump is essential. A row of boulders is located at the basin end to create a sill transition to the downstream invert elevation.

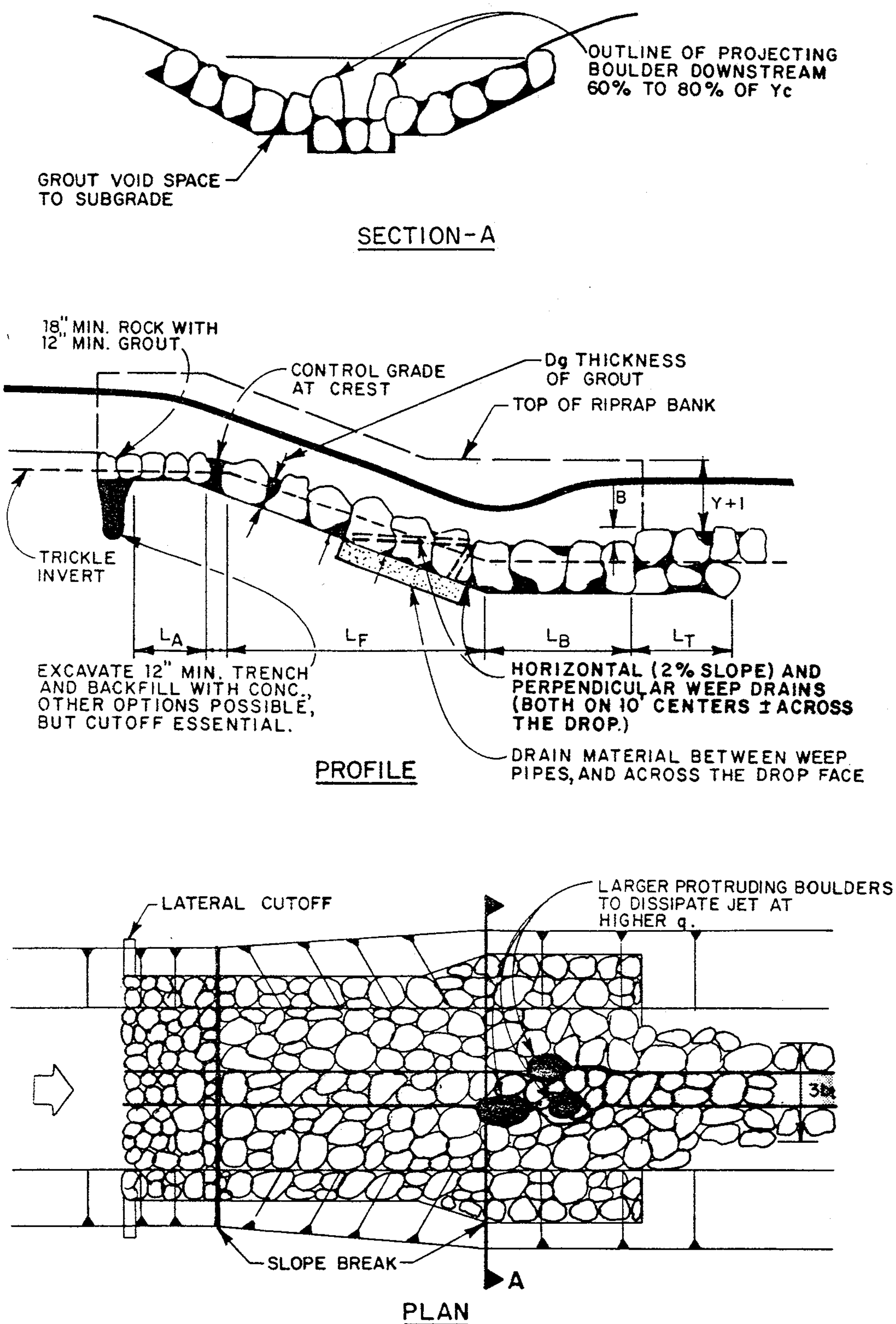


Figure XII-4

GSB - Grouted Sloping Boulder Drop

g. The selection of face slope is largely a hydraulic matter related to jump stability. Generally, do not use slopes steeper than 4:1 without extensive analysis. Concerns regarding the length of the basin are similar to those expressed for the SLR drops.

BC - BAFFLE (APRON) CHUTE - USBR DESIGN, XII-5 (REF. 34)

a. Maximum design q is 60 cfs/ft, optimal performance is at 35 - 40 cfs/ft.

b. An upstream channel transition section with vertical wing walls constructed 45° to the flow direction causes flow to contract approaching the rectangular chute section.

c. The transition is followed by a concrete rectangular flow alignment apron, typically 5 feet in length. Entrance velocity V, should be as low as practical or $V_1 = (gq)^{1/3}$ (see Figure XII-6).

d. The chute section (baffled apron) is concrete with baffles of height (H) equal to 0.8 to 0.9 times critical depth. The chute face slope is 2:1 for most cases, but may be reduced for low drops. Baffle pier width should be between 1.0 to 1.5 times H, and spacing between rows should be 2 times H.

e. Four rows of baffle piers are required to establish full control of the flow, although fewer rows have operated successfully. At least one row of baffles are buried in riprap where the chute extends below the channel grade. Rock protection, assumed here as Type M, continues from the chute outlet to a distance of approximately 4 H at a depth of 1.75 feet, or as necessary to prevent eddy currents from undermining the walls.

f. Upstream transition and apron side wall height is as required by backwater analysis. Chute side walls are recommended to be 3 times the baffle height.

g. There are lower basin wing walls constructed normal to the chute side walls at the outlet to prevent eddy current erosion at the drop toe. These transition walls are of a height equal to the channel normal depth + 1 foot and length sufficient to inhibit eddy current erosion.

h. All concrete walls and footer dimensions are determined by conventional structural methods. Cutoff walls and underdrain requirements are determined by seepage analysis.

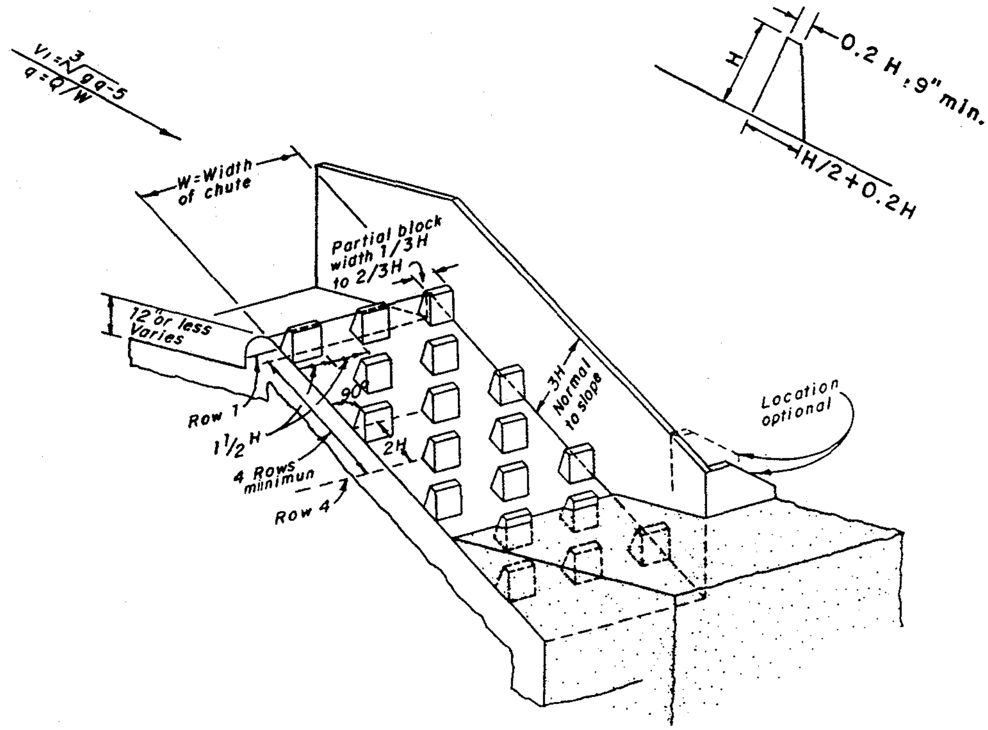


Figure XII-5

BC - Baffled (Apron) Chute

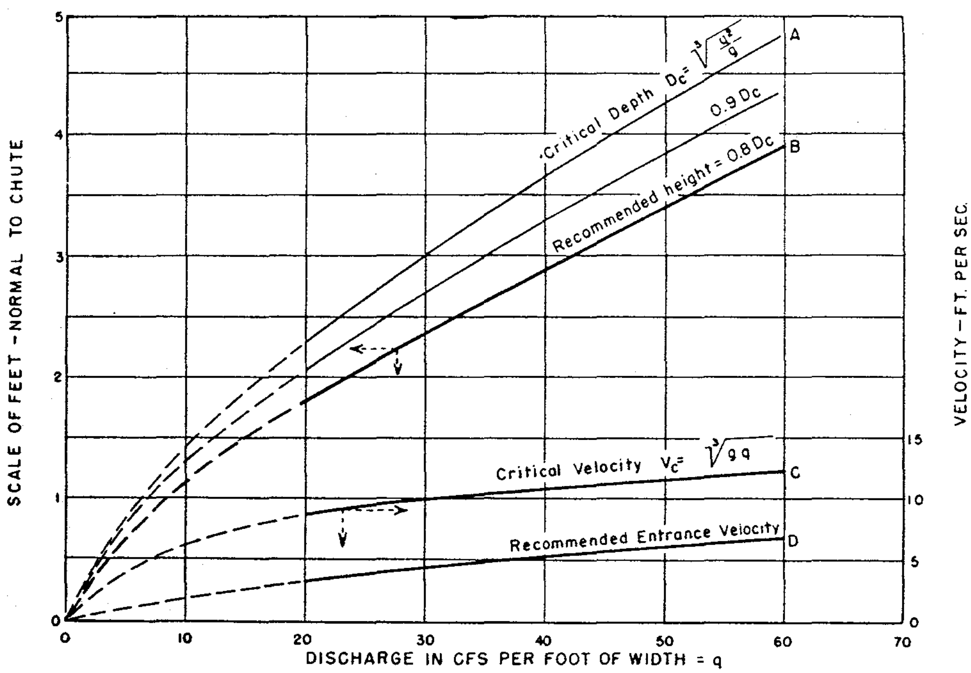


Figure XII-6

Recommended Baffle Pier Heights and Allowable Approach Velocities (ref. 34)

i. The trickle flow channel should be maintained through the apron, approach and crest sections. It may be routed between the first row of baffle piers. The trickle channel should start again at the basin rock zone which should be slightly depressed and then graded up to transition to the downstream channel and focus on low flows to the trickle.

Figure XII-7 illustrates details of one concept to take the trickle channel through the crest.

j. Also shown is the layout of a hard stilling basin, used in Tulsa because of significant problems with vegetation and nuisance conditions that grows in riprap profusely.

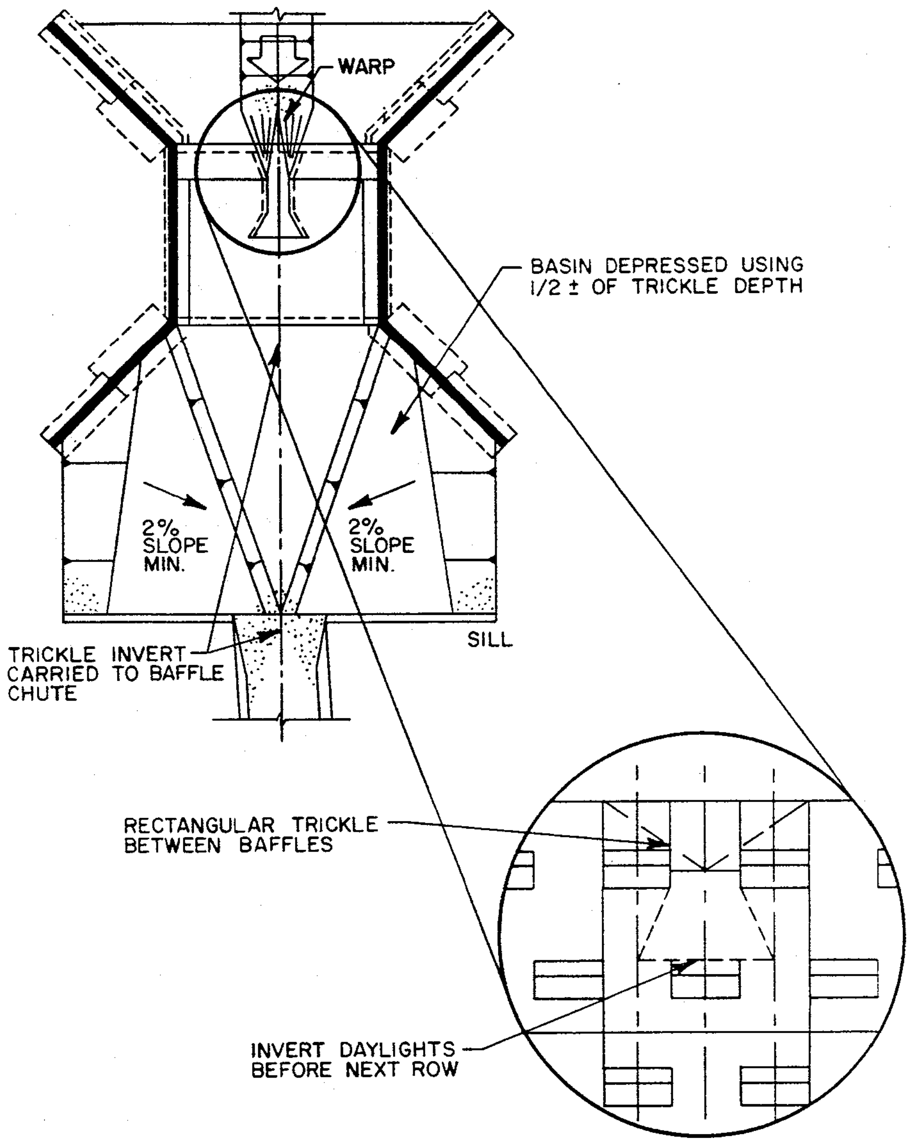


Figure VII-7

BC - Example Baffle (Apron) Chute Details for Trickle Channel and Hard Stilling Basin

VHB - VERTICAL HARD BASIN (SEE FIGURE XII-8)

a. Many alternative designs, variations and different combinations of materials may be grouped into this basic design category. The SCS Manual (ref. 54) is useful for all concrete structures, although adaptations are necessary for the trickle channel and low flow controls. Other concrete configurations are feasible (see Section IV).

b. The rock lined approach length ends abruptly at a structural retaining crestwall which has a nearly rectangular cross-section and trickle channel section.

c. Crestwall and footer dimensions are determined by conventional structural methods. Underdrain requirements are determined from seepage analysis.

d. Chow (ref. 10) makes a brief presentation for the "Straight Drop Spillway" which applies here. Separate analysis would need to be undertaken for the trickle channel area and the main channel area as discussed previously. Add subscript $_t$ for the trickle channel area and subscript $_m$ for the main channel area in the following equations. The drop number D_n is defined as:

$$D_n = q^2/(g\ h^3) \qquad \text{XII.7}$$

At the condition of a hydraulic jump that immediately occurs at the point where the nappe hits the basin floor, the following variables are defined as:

$$L_d/y_f = 4.3\ D_n^{0.27} \qquad \text{XII.8}$$

$$y_p/y_f = 1.0\ D_n^{0.22} \qquad \text{XII.9}$$

$$y_1/y_f = 0.54\ D_n^{0.425} \qquad \text{XII.10}$$

$$y_2/y_f = 1.66\ D_n^{0.27} \qquad \text{XII.11}$$

These variables are indicated on Figure XII-8.

L_d is the length from the crestwall to the impigement of the jet on the floor, y_p is the pool depth under the nappe downstream of the crest, y_1, is the flow depth on the basin floor just below where the nappe contacts the basin and y_2 is the required tailwater depth to cause the jump to immediately occur.

In the case where the tailwater does not provide a depth equivalent to or greater than y_2 the jet will wash downstream at supercritical flow until its specific force is sufficiently reduced to allow the jump to occur. This requires a Water Surface profile analysis. And because there are two general locations to check, there is another iterative step because any change in tailwater effects the stability of the jump in both locations.

e. The basin floor elevation is depressed a depth variable with drop height and practical for trickle flow drainage. It is constructed of concrete or grouted rock. Either would have to be evaluated for the hydraulic forces and seepage uplift.

f. There is a sill at the basin end to bring the invert elevation to that of the downstream channel and side walls extending from the crestwall to the sill. The sill is important in causing the hydraulic jump to form in the basin.

g. Water surface profile calculations indicated base widths of the rectangular crest which are less than that of the channel, produce high flow velocities requiring unreasonable extensions of both the basin length and upstream rock protection. Roughness in the basin area can reduce the basin length required to contain the hydraulic jump, which is an advantage of the grouted rock shown here.

h. Large boulders and meanders in the trickle are shown to help dissipate the jet, and rock is extended downstream.

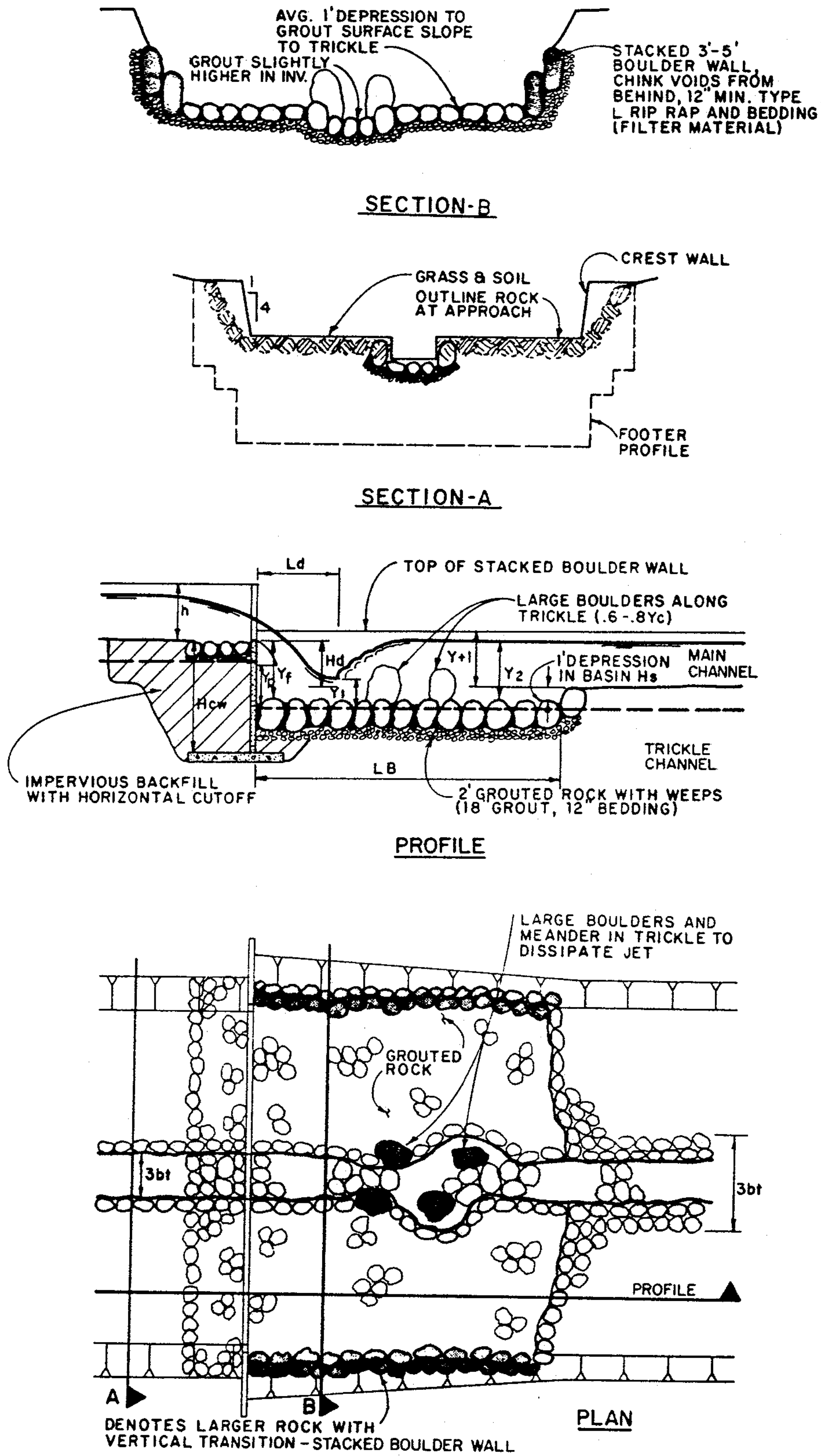


Figure XII-8

VHB - Vertical Hard Basin Drop

SECTION XIII
COST CONSIDERATIONS

INTRODUCTION

The preceeding survey of existing drop structures in the Denver area illustrates the tremendous diversity in construction methods and design approaches which have been applied. In many cases, the specific site requirements may dictate the direction of drop structure design to be taken.

Cost effectiveness and present worth cost analyses are useful tools for screening alternatives. There is a temptation to simply look at the costs of projects in place. However, several problems arise from using case history records for cost comparisons. Hydraulic performance is frequently difficult to evaluate since many existing prototype structures may not have been tested by a high intensity, low frequency flood event. When cost records are available, it is often impossible to separate the drop structure costs from other project site work. Bidding summaries may not represent the actual costs incurred and are usually oriented to a site specific bias from which it is difficult to directly ascertain cost data.

The following cost analysis is intended to provide some projected economic guidelines which may be adjusted to specific situations and combined with other decision factors to assist the design engineer in selecting an optimal approach.

METHODS

A standardized model design procedure was employed to reduce the inherent uncertainties and create an equitable basis of comparison between structural design alternatives. Typical design configurations were developed for several types of drop structures which could be compared over a range of sizes and design flows. This process consisted of the following stages:

1. Delineation of the evaluation matrix of structure design types, channel discharge range and vertical drop height ranges to be considered.

2. Establishment of the theoretical hydraulic parameters present in the drop and adjacent grass-lined channels for the design discharge range.

3. Formulation of the structural design parameters to allow computations of the corresponding material quantities required for each drop size in the valuation matrix.

4. Compilation of the material quantities and application of unit costs to calculate estimated capital costs for each case considered.

5. Identification of approximate maintenance costs and computation of the present worth for each configuration.

The five basic drop structure designs outlined in Section XII were evaluated in this cost analysis. In addition to these, the sloping face, loose riprap design discussed in Section V was included. Critical dimensions for this design (herein denoted; SRR) were directly intepreted from UDFCD design critiera (ref. 63). Refer to Figure V-1 for the SRR drop and the figures in Section XII for the other conceptual layouts.

Model designs were developed to represent the average or typical structure so that costs could be estimated. The following paragraphs are intended to outline the premises used in the cost estimates. While the "synthetic" designs developed for this analysis follow the basic design criteria, they should not be used as a substitute for proper design procedures.

Evaluation Cases

Channel flow discharges of 500, 1500, 3000, and 7500 cfs and drop heights of 2, 4, 8, and 12 feet were considered as the basic size matrix. This matrix range encompasses the common design range needs and is within the practical limitations for grass-lined channels of the Front Range area. Combinations of 500 cfs, 2 ft. drop (smallest) and 7500 cfs, 12 ft drop (largest) were the matrix extremes. A "base case" of 1500 cfs and 4 ft drop height was identified to be the most common or typical structure configuration.

The present UDFCD criteria for grass-lined channels allows a maximum flow velocity of 7.0 fps and a maximum flow depth of 5.0 feet for erosion resistant soils. To establish a comparative standard, a slightly more conservative normal depth of 4.5 feet and maximum velocity of 7.0 fps were assumed to determine the channel dimensions. Table XIII-1 presents those dimensions.

Table XIII-1

Standard Channel Hydraulic Parameters

Q	b	n	S_o	Y_n	V_n	q	Y_c
500	20	.035	.003	3.49	4.22	14.73	2.29
1500	45	.035	.003	4.48	5.32	23.83	2.97
3000	85	.030	.003	4.44	6.57	29.17	3.21
7500	225	.030	.003	4.43	6.98	30.92	3.19

Q = Channel discharge; ft^3/sec.
b = Channel base width; ft.
n = Mannings roughness coefficient
S_o = Channel invert slope; ft/ft
Y_n = Normal flow depth; ft.
V_n = Average flow velocity; ft/sec
q = Unit discharge = $Yn * V_n$
Y_c = Critical depth at crest; ft.

Water surface profile computations were performed in both upstream and downstream directions to determine the maximum flow depth, velocity and jump location for different channel and drop structure configurations. A channel constriction was assumed only in the Vertical Hard Basin (VHB) and Baffle Chute (BC) designs. The Vertical Hard Basin (VHB) had a transition to rectangular shape at the crestwall. A slight base width constriction was configured into the BC design to produce a typical entrance unit flow of 40 - 43 cfs/ft.

Basin lengths, face slopes, trickle protection lengths and rock sizing were determined for the improved sloping loose rock drops, (SLR), and grouted sloping boulder, GSB, designs using the preceeding design criteria. Both SRR and VRR riprap designs were configured per UDFCD design criteria.

All of the structural wall thickness and footer dimensions were estimated with assistance from structural engineers. Free standing walls were assumed to be buried 3 ft. below the rock excavation level. Excavation was assumed to be the cross-sectional channel area plus riprap and bedding depth carried through the drop section. Excavation for walls and footings was added to this according to the design.

Analysis Technique

These design criteria were formulated into spreadsheet software and expanded to cover the evaluation matrix. Sixteen different configurations (combination of drop heights and discharges) for each of the six design categories were evaluated. Quantities of major construction materials were computed for each configuration and then compiled into quantity summaries. Examples of quantity calculation sheets for the BC and GSB "base case" configurations are shown in Tables XIII-2 and XIII-3. The calculation format derived for the other structure designs is varied somewhat depending on specific design requirements.

Simplifying assumptions were made to allow direct comparison between different drop structure designs. Only costs directly associated with the drop structure were considered; no embankment grading, channel lining or any other site work on the upstream or downstream channels were included in the calculations. Quantities of graded rock, sized boulders, grout, concrete and excavation were determined based on the design and sizing parameters. Only these five primary costs were considered; other costs were assumed to be relatively minor, and were neglected. Extraordinary labor, specialized equipment, training or expert consultation costs were not included. Deficiencies in hydraulic performance for certain designs have been discussed previously and these problems are reflected in the maintenance cost estimates.

Table XIII-2

Grade Control Drop Structure Evaluation

USBR Baffle Chute Design

Drop Constants:

Hd=	4.00	Q=	1500	Zf=	2.00
So=	0.003	n=	0.035	Zs=	4.00

Trapazoidal Channel:

b1=	45 ft	Vn=	5.32
Yn=	4.48 ft	q1=	23.84
A1=	281.88 ft2	E=	4.92
P1=	81.94 ft	T1=	80.84
T1 at Height h =			93.00

Rectangular Chute:

b2=	35 ft	Vc=	11.13
Yc=	3.85 ft	qc=	42.86
A2=	134.75 ft2	E=	5.77
P2=	42.70 ft	Yn=	7.38
Backwater Max Ya =			5.55

Concrete Quantity Computations:

Hb = 3.08 ft Wb = 3.85 ft (USBR Criteria)
Rows of Baffle Piers = 3.7 rows
Baffle Piers / Row = 4.5 piers
Total Volume in Baffles = 701.04 ft3

h = 6.0 ft = Height above crest from backwater

Lt =	29.00 ft			Th =	10 in
Lwt=	41.01 ft	Hwt=	9.00 ft	Awt=	891.13 ft2
La =	5.00 ft	Hwa=	6.00 ft	Awa=	60.00 ft2
Lf =	22.72 ft	Hwc=	9.24 ft	Awc=	419.84 ft2
Lwb=	29.00 ft	Hwb=	12.24 ft	Awb=	659.30 ft2

Volume in Side Walls = 1691.89 ft3

Aa = 220 ft2 Af = 1110.02 ft2 Acw= 390
Volume in Chute Floor = 1433.35 ft3 Th = 10 in

Total Concrete Volume Estimate = 3826 ft3

Rock Quantity Computations:

Type "M" Rock min. depth = 1.75 ft
Lb = 8 x Hb = 24.64 ft Ls = 22.59 ft

Transition rock length = 15 ft
Volume in Transition = 1312.50 ft3
Volume in Chute Basin = 3272.58 ft2

Total Rock Volume Estimate = 4585 ft3

Excavation Quantity Computations:

Ae1 = Channel Section; b1 for (Yn+1)+Dr+Db = 614.74 ft2
Ae2 = Apron Section; b2 for (Yn+1) + 1ft = 237.76 ft2
Ae3 = Chute Section; b2 for 3Hb + 1ft = 376.88 ft2

Total Excavation Volume Estimate = 30087 ft3

Table XIII-3

```
==========================================================================
    GSB2          Grade Control Drop Structure Evaluation

                  Sloping Face, Grouted Boulder Type Drops
==========================================================================
Drop Constants:
               Hd=    4.00 ft     Q=    1500       Zf=    4.00

               So=  0.0030        n=   0.035       Zs=    4.00
--------------------------------------------------------------------------
Input Variables:
      b1=       45 ft                    b2=       45 ft
      Yn=     4.48 ft    Vn=     5.32    Yc=     2.97 ft    Vc=     8.88
      A1=   281.88 ft2   q1=    23.84    A2=   168.93 ft2   qc=    26.37
      P1=    81.94 ft     E=     4.92    P2=    69.49 ft     E=     4.19
==========================================================================
Boulder Quantity Computations:      Basin B =    0.50 ft depth
                        Lf=   18.55 ft    Ls=   22.59 ft

              Main Channel     Trickle Channel
              Wb1=   84.19       Wt=    6.00          (MWE Criteria)
              Wb2=   84.19                            (MWE Criteria)
               Lb=   17.90       Lb=   53.30          (MWE Criteria)
               Dr=    2.66       Dr=    2.66          (MWE Criteria)
          Volume =    9283 ft3          1227 ft3

         Total Boulder Volume Estimate =        10510 ft3
--------------------------------------------------------------------------
Rock Quantity Computations:

         Type "M" rock on approach section =     1.75 ft depth
         Loose rock approach length =    La =       5 ft

         Total Rock Volume Estimate =              789 ft3
--------------------------------------------------------------------------
Grout Quantity Computations:
         Note: Grout Fills 35% Rock Void Space to a Depth of .75 x Dr
         Grout Depth   Dg =     2.00 ft

         Total Grout Volume Estimate =            2759 ft3
--------------------------------------------------------------------------
Concrete Quantity Computations:
               10 inch Cutoff Wall thickness

         Hcw = ( B + Dr + Db + 3 ) =                Hcw=    7.16 ft
         Wcw = Foot Width =     0.00   x Hcw =      Wcw=    0.00 ft
         Acw = Cutoff Surface Area =  645.75 ft2

         Total Concrete Volume Estimate     =        538 ft3

--------------------------------------------------------------------------
Excavation Quantity Computations:
         Ae1 = Sectional Area at (Yn+1) + Dr + Db     =   696.81 ft2
         Ae2 = Sectional Area at the Drop Crest       =   696.81 ft2
         Extra Excavation for Trickle        =   572.98 ft3

         Total Excavation Volume Estimate  =    36172 ft3
--------------------------------------------------------------------------
```

Unit costs were based on recent project proposal records and information provided from material suppliers. Refer to Table XIII-4 which includes the unit price schedule used in this analysis.

Table XIII-4
Unit Costs
All Amounts in 1986 Dollars

Rock "M"	30.00/ton	Grout	100.00/cu.yd.
Rock "H"	30.00/ton	Concrete	300.00/cu.yd.
Rock "VH"	35.00/ton	Excavate	2.50/cu.yd.
Boulders	40.00/ton		

Conversions: 1.8 ton/cu.yd. 27 ft. 3/cu.yd.

Prices include closely related materials and routine labor such as: gravel bedding and placement included in loose rock costs; structural forms and reinforcement with concrete; pumping and settling work with grout; and sizing and placement for boulders. Excavation volumes calculated were conservative to allow for backfill in some areas. These unit prices were applied to the quantity summaries along with conversion factors to produce the capital construction cost for each structure design and configuration evaluated.

UDFCD has determined that loose rock drops should be constructed no higher than four vertical feet due to stability problems. Vertical drops greater than four feet raise safety concerns in urban areas, therefore, the eight and twelve foot drop configurations for these structures were considered as multiples of the four foot drop costs cost.

Maintenance Costs

Maintenance costs were difficult to determine due to the random nature of flooding occurances and the limited length of records available. Maintenance was defined as routine, restorative and rehabilative depending on the type of work necessary to sustain or improve the appearance, safety and function of the structure. Major categories of maintenance work were identified to be: replacement of displaced rock; earthfill of eroded areas; removal of debris, graffitti removal; repairs to structural members; and removal of silt entrapped in the drop basins. The specified time related cost criteria varied accordingly:

1. Rock Replacement: A one time restorative cost occurring at the tenth year based on estimated rock displacement volume and field experience.

2. Debris Removal: Routine annual maintenance estimated for the typical "base case" and proportioned by discharge and drop height.

3. Erosion Backfill: Periodic maintenance every ten years estimated for the "base case" and proportioned by discharge and drop height.

4. Graffiti Removal: Periodic maintenance every ten years. The initial estimate based on the exposed surface area and proportioned by the design discharge range only.

5. Structural Repairs: Engineered estimate based on the concrete volume and repair average for all structures; 2% failure occurring at the fifth year, and 1% due to wear at the 25th year.

6. Silt Removal: Periodic maintenance every ten years estimated for the "base case" and proportioned by discharge and drop height.

For evaluation purposes all maintenance costs were considered to be average expected values, recognizing that structures may vary widely in the amount of maintenance required. Costs were estimated for the typical "base case" of 1500 cfs and 4 foot drop height through a combination of practical experience, engineering expertise and cooperative effort between MWE and UDFCD personnel. Values for this case were proportioned to derive the cost estimates for other size configurations.

Present Worth Analysis

All maintenance costs were converted to present worth (PW) amounts by applying the appropriate discount rate factors. Table XIII-5 contains the maintenance cost estimates for the base drop configuration and the present worth costs derived using a 5% discount rate.

A great deal of controversy surrounds the selection of discount rate for use in economic studies, particularly when public funds are involved. Public capital expenditures cannot be depreciated against taxes the way private capital outlays are. Federal government agencies use a rate based on the 15 year moving average bond return, constrained to a maximum rate change of 0.25% in any year. The federal rate was 8-5/8% as of October, 1986. This computation method has a tendency to lag the real growth rate, especially during years of high inflation. Disparities between the projected discount rate and prevailing return rates have created funding projection problems for public agencies. In an effort to deal with this problem some state agencies have adopted a rate based on the real return on equity for a certain long-term economic analysis. Recently, this rate was reported to be within approximately 2% net bond return or 3% paid to debt service.

James and Lee (ref. 68) have defined: "The ideal discount rate would achieve a rate of capital formation maximizing total social welfare". This conceptual definition points out the goal of flood control improvements but gives little assistance in selecting an optimum rate.

For these reasons, a sensitivity approach was taken regarding discount rate selection. A range of discount rates were applied to the maintenance costs. The present federal rate of 8-5/8% and the low rate of 2% were compared as boundary conditions. An intermediate rate of 5% was incorporated into the total cost comparisons. The design life was held constant; equal to 50 years for all alternatives evaluated.

Table XIII-5

Drop Structure Evaluation
Maintenance Cost Computations

Vertical Drop Height:	Hd =	4	ft
Design Flow Discharge:	Q =	1500	cfs
Discount Rate:	i =	5.00	%
Project Design Life:	N =	50	years

Maintenance Category	Sloping Rock SRR	Vertical Rock VRR	Large Rock SLR	Grouted Boulder GSB	Baffle Chute BC	Vertical Hard VHB
Replace Rock:	One time cost at tenth year					
cost	$12,547	$2,965	$2,648	$2,500	$459	$1,952
net PW	$7,703	$1,820	$1,626	$1,535	$282	$1,198
Debris Removal:	Annual Maintenance					
cost	$100	$100	$100	$90	$115	$90
net PW	$1,826	$1,826	$1,826	$1,643	$2,099	$1,643
Erosion Backfill:	Periodic every ten years					
cost	$1,000	$400	$500	$200	$200	$200
net PW	$1,451	$581	$726	$290	$290	$290
Graffitti Removal:	Periodic every ten years					
cost	$0	$200	$0	$0	$240	$200
net PW	$0	$290	$0	$0	$348	$290
Structure Repair:	Fail at fifth year, Wear at 25th year					
fail 2%	$134	$758	$157	$120	$850	$415
wear 1%	$67	$379	$79	$60	$425	$208
net PW	$125	$706	$146	$112	$792	$386
Silt Removal:	Periodic every ten years					
cost	$0	$150	$150	$150	$0	$150
net PW	$0	$218	$218	$218	$0	$218
Total Net PW:	$11,105	$5,440	$4,541	$3,798	$3,811	$4,026
Total Net AW:	$608	$298	$249	$208	$209	$221
Design Reference:	UDFCD	UDFCD	MWE	MWE	USBR	MWE

A secondary cost comparison was made illustrating an optimization procedure whereby the lowest cost (optimal) design of three possible VHB designs was selected for inclusion in the overall cost analysis. The three conceptual designs essentially compared different treatments of the basin area. The first case, designated VHB2, is an all concrete basin with side walls connected at a height equal to the top of the crestwall at one end, and decreasing in height to the level of the concrete sill at the basin end. The second design, VHB3 is very similar to the first, except the basin side walls are lower at the crestwall end to equal the channel condition of normal depth Yn, + 1 foot of freeboard. Lower side walls require a wider crestwall to allow grading up from the side wall top to the crestwall end. The last configuration compared, VHB4, has a modified basin area consisting of grouted boulder floor and basin end sill. Basin side walls are constructed of stacked boulders, sufficient in height to contain the tailwater depth at the crestwall and reduced to one row at the sill end (Figure XII-8). The crestwall was then sized long enough to permit embankment grading from the boulder sides to the wall ends. Water surface profile computations proved the basin length could be reduced considerably if the floor roughness was increased from a Mannings' "n" of 0.02 for concrete to 0.04 for large grouted rock. This configuration was found to have the lowest estimated capital cost of the three.

COMPARISON RESULTS

The results of the capital cost comparison are summarized in Table XIII-6. Values are in 1986 dollars, relevant to the Denver/Front Range area. Capital cost information may be helpful in estimating construction costs, however, these results should not be used for alternative selection decisions. Unit costs may be adjusted by refering to the quantity summary Tables in Appendix C. Table XIII-7 contains the results of the vertical hard basin comparison mentioned previously. It is feasible to adapt this information to consider material substitutes, design changes or hydraulic configurations as a means of design refinement. For example, the effect of using sheetpile or timbers in the cutoff wall could be examined by replacing the concrete component cost with substitute material formulas, then expanding over the size matrix. Careful attention should be directed toward the model assumptions when incorportaing these results into further studies.

Table XIII-6

Drop Structure Evaluation Capital Cost Comparison Drop Configurations: Hd vs Cost				Initial Construction Capital Costs		
	SRR Sloping Rock	VRR Vertical Rock	SLR Large Rock	GSB Grouted Boulder	BC Baffle Chute	VHB Vertical Hard
Q = 500 cfs						
Hd = 2ft	$15,300	$22,017	$20,889	$20,028	$29,587	$18,363
Hd = 4ft	$18,032	$45,867	$32,226	$24,638	$31,950	$27,583
Hd = 8ft	$36,064	$91,734	$64,451	$33,170	$36,678	$55,166
Hd = 12ft	$54,097	$137,601	$96,677	$40,829	$41,405	$82,749
Q = 1500cfs						
Hd = 2ft	$37,712	$41,189	$41,675	$40,828	$49,992	$30,274
Hd = 4ft	$44,376	$71,714	$63,847	$49,151	$54,470	$44,113
Hd = 8ft	$88,751	$143,428	$127,694	$74,437	$63,426	$88,226
Hd = 12ft	$133,127	$215,142	$191,542	$89,755	$72,382	$132,340
Q = 3000cfs						
Hd = 2ft	$69,032	$58,064	$75,020	$73,583	$79,116	$50,477
Hd = 4ft	$81,257	$100,654	$109,628	$86,779	$86,725	$70,760
Hd = 8ft	$162,513	$201,308	$219,256	$112,512	$101,943	$141,521
Hd = 12ft	$243,770	$301,962	$328,885	$134,398	$117,161	$212,281
Q = 7500cfs						
Hd = 2ft	$152,108	$117,597	$156,908	$157,574	$182,923	$109,524
Hd = 4ft	$185,768	$199,560	$223,717	$184,373	$199,926	$152,363
Hd = 8ft	$371,536	$399,119	$447,433	$237,310	$233,930	$304,726
Hd = 12ft	$557,304	$598,679	$671,150	$282,594	$267,934	$457,090
Reference:	UDFCD	UDFCD	MWE	MWE	USBR	MWE

note: Loose rock and vertical drops greater than 4ft height are considered as multiples of the 4ft drop structure cost.

Table XIII-7

Grade Control Drop Structure Evaluation

Vertical Hard Basin Design Comparision

	VHB2	VHB3	VHB4
Q = 500			
Hd=2 ft	$19,168	$22,240	$19,441
Hd=4 ft	$32,630	$39,938	$28,955
Hd=8 ft	$55,654	$71,436	$51,197
Hd=12ft	$80,641	$105,700	$74,607
Q = 1500			
Hd=2 ft	$36,055	$37,863	$32,147
Hd=4 ft	$61,991	$68,018	$46,521
Hd=8 ft	$110,583	$124,806	$77,842
Hd=12ft	$151,269	$172,632	$111,499
Q = 3000			
Hd=2 ft	$61,105	$63,488	$53,777
Hd=4 ft	$108,719	$115,849	$74,928
Hd=8 ft	$194,856	$210,617	$121,824
Hd=12ft	$254,889	$277,300	$167,901
Q = 7500			
Hd=2 ft	$132,265	$134,269	$116,647
Hd=4 ft	$227,519	$233,969	$161,521
Hd=8 ft	$393,196	$408,161	$250,092
Hd=12ft	$519,992	$542,264	$343,916

Reference:

VHB2 = Simplified concrete design with basin chute walls full height of the crestwall drop.
VHB3 = Simplified design with basin side walls only as high as channel depth; crestwall expanded to grade.
VHB4 = Simplified design as above with grouted rock basin and side walls; shorter basin due to friction increase.

Note:

In populated urban and residential areas the vertical drop is a safety concern. For these areas four feet drop is the maximum permitted height and the 8 and 12 foot drops should be regarded as multiples of the four foot drop cost. In this comparison costs for the higher drops were computed for a single structure so that possible cost trade-off points could be identified.

Equivalent worth and sensitivity analyses were employed in the maintenance cost comparison. Equivalent worth methods are useful when attempting to evaluate alternatives which have different costs occurring at different times and intervals. The sensitivity of projected maintenance costs to discount rate change is displayed in Figures XIII-1 and XIII-2. Shaded bar sections in these figures indicate the present worth (PW) costs discounted at 8-5/8% while the full bar heights reflect PW costs at 2%.

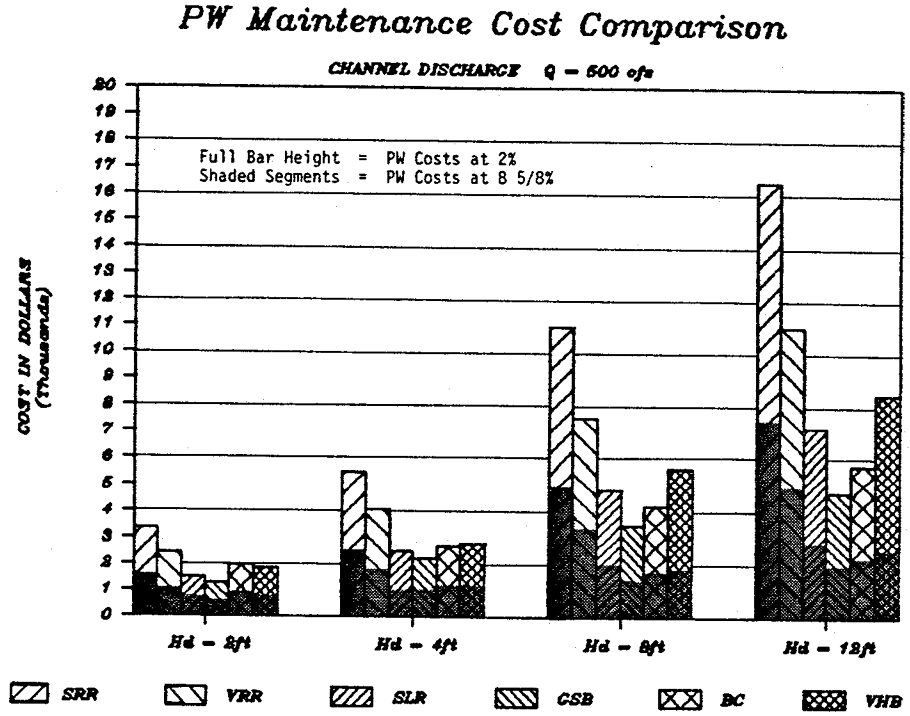
The differential in costs produced by these rate extremes gives an indication of the total funding shortfall potential if a rate disparity of this magnitude were to occur in projections. Even though it is not likely that a constant disparity would persist for the entire 50 year design life, the reasons for funding concerns are apparent. Drop structure designs with high maintenance requirements are less desirable, therefore maintenance costs should be a decision factor in alternative selection.

The total present worth costs of the six drop structure designs were compared over the discharge and drop height matrix. The results of this comparison are illustrated by bar charts in Figures XIII-3 and XIII-4. In these figures total costs are represented by the full bar heights, while the PW maintenance costs at 5% and capital cost components are represented by the dark and light regions respectively. All values are in terms of 1986 dollars.

Discount rate was shown to have a significant effect on PW maintenance costs, however, the PW maintenance cost component appears to be minor relative to the capital costs for all but the largest loose rock extremes considered. It is evident that even discounting at 2% would produce little additional change in the overall cost effectiveness rankings.

Direct interpretation verified some of the trends which were anticipated. Less structural, simple drop designs are relatively inexpensive at smaller sizes. Conversely, the baffle apron drops are more cost effective for drops over 8 feet. The VHB design appears to be favorable for smaller low drops. Grouted boulders GSB, and Baffle Chute, BC, are more cost effective for higher, large structures. Loose rock

Figure XIII-1



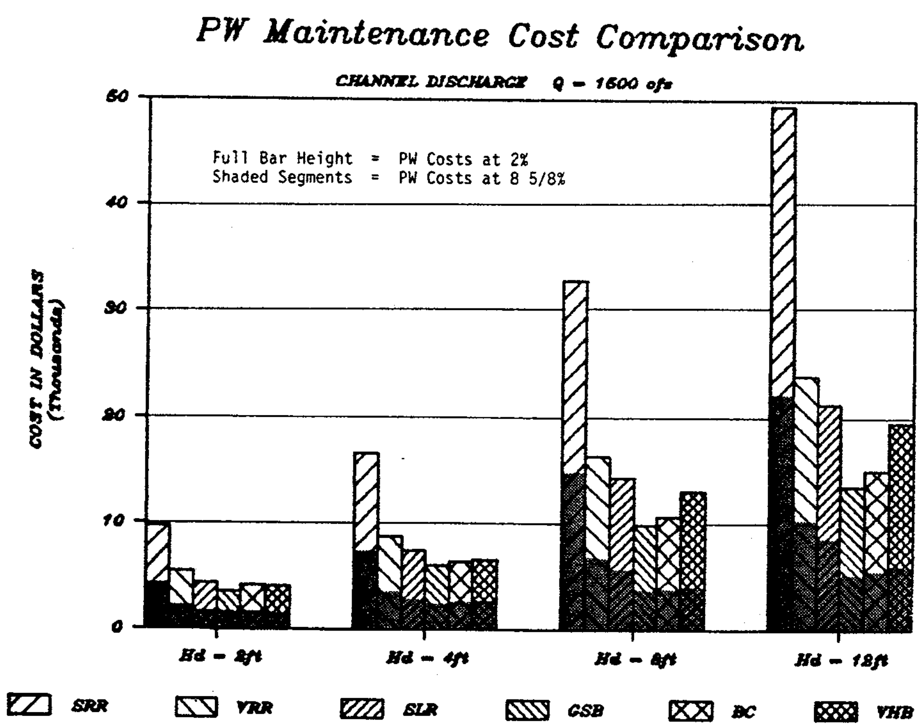
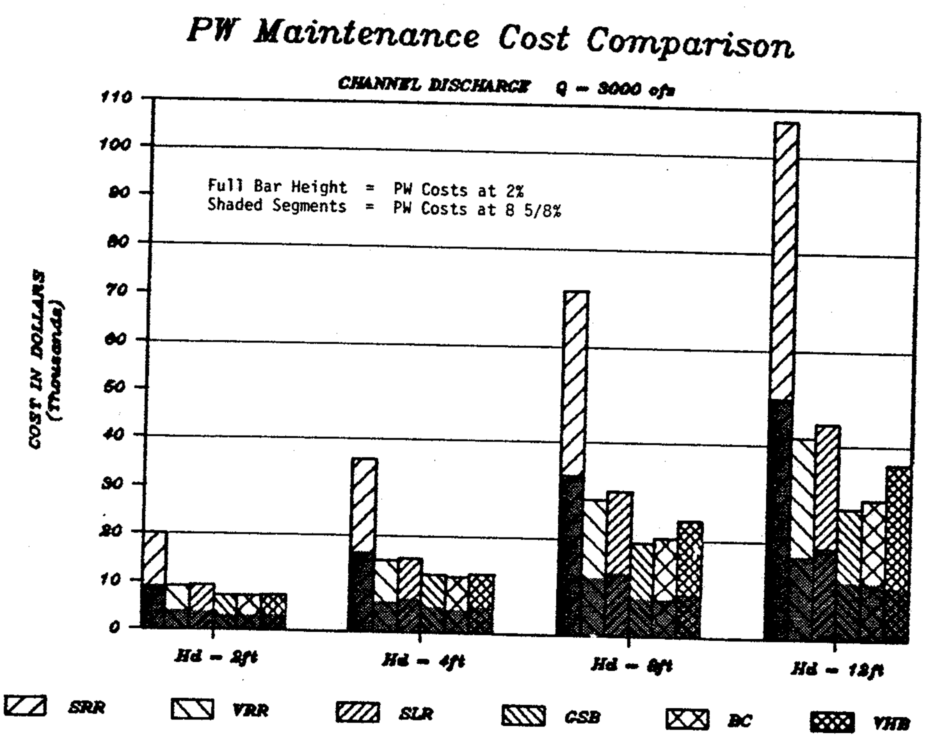
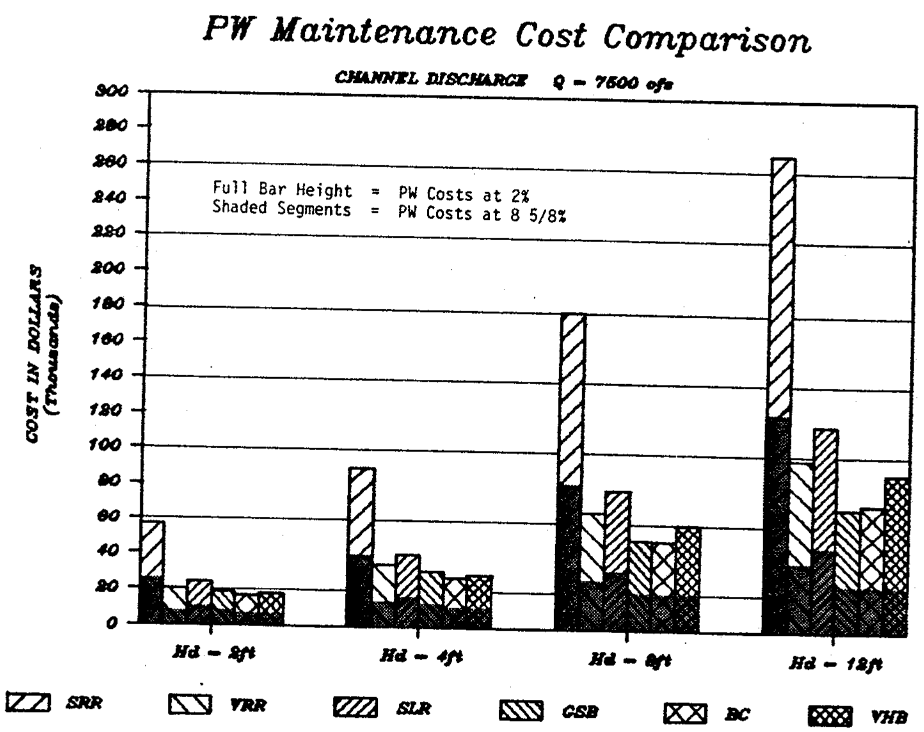


Figure XIII-2





drops are prohibitive at the higher drop sizes due to the 4 foot height restriction. In fact, they are only cost effective at the smallest application extremes due to relatively high maintenance costs.

There is great concern about the assumed probability of ongoing problems with SRR drops, and to some degree with the improved SLR drop. It is re-emphasized that these riprap drops have an unavoidable tendancy for continual rock movement and associated maintenance problems. Maintenance costs were estimated (ref. 43) since an extensive scientific probability study was beyond the scope of this project. If there were strong continued interest in riprap structures it would be advisable to undertake this type of investigation.

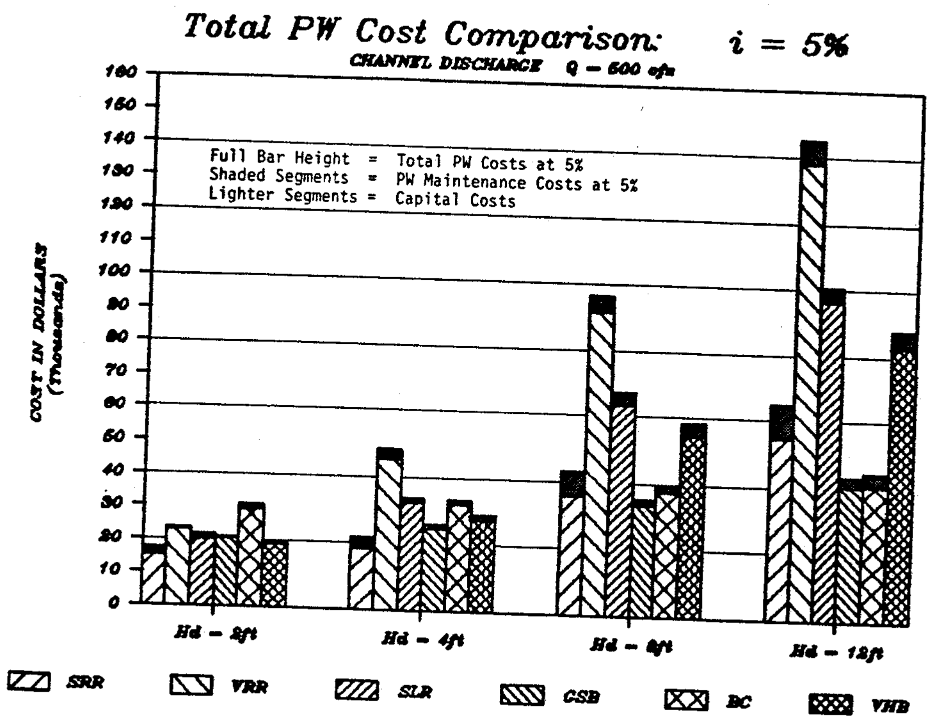
These cost effectiveness comparisons may be applied to help screen drop structure alternatives which are similar in design to those considered in this study. Figures XIII-3 and XIII-4 are useful for comparing costs within one of the four design discharge levels evaluated. Charts may be used together to interpolate values for structure configurations which are intermediate in either the discharge (channel width) or drop height directions. Interpolation may also be accomplished using the data tables in Appendix C. The overall total cost position relationships are more clearly displayed in Figure XIII-5 which has all bars drawn at a common scale.

When alternative costs are very close together, secondary decision criteria should be considered. It is important to remember that the values presented here are only the hard costs associated with the structure. Secondary decision factors such as local availability of materials, ease of design and construction, safety, aesthetics, or risk failure are also important.

To convert the matrix of alternatives into economic efficiency, the total PW costs were divided by the corresponding drop height and discharge to yield: PW cost/cfs/ft of drop. These concepts may appear to be somewhat abstract but have important practical consequences since they are a measure of relative value.

Several economic relationships are illustrated in Figures XIII-6 and XIII-7. In Figure XIII-6 the efficiency related to drop height is compared for the 6 alternative designs.

Figure XIII-3



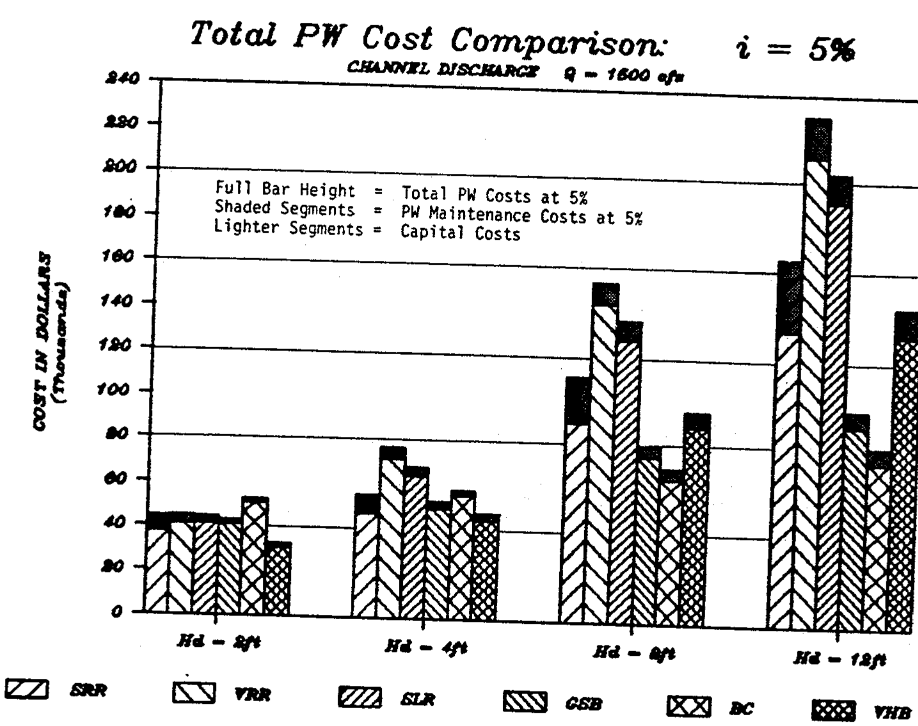
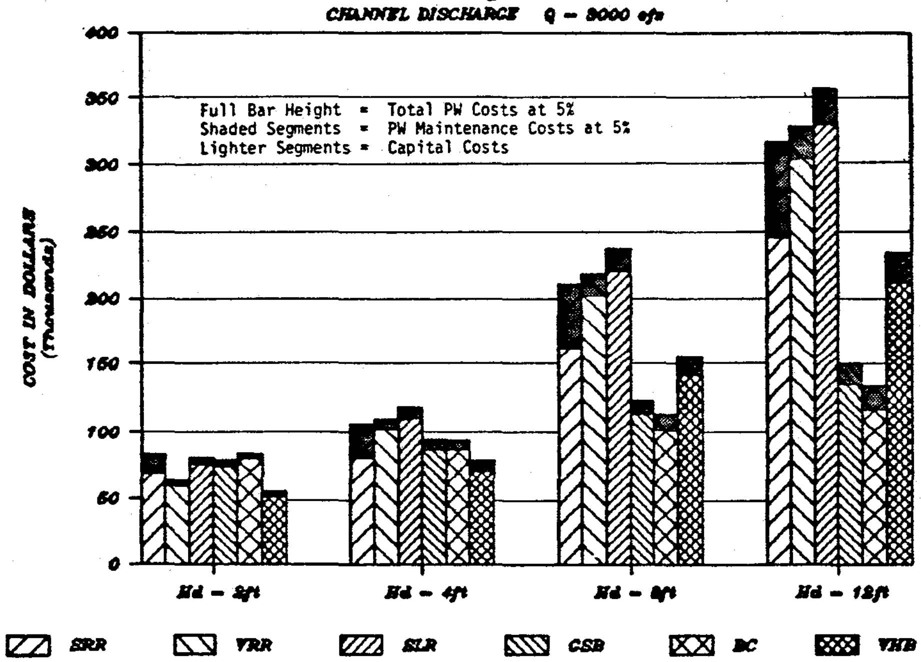


Figure XIII-4

Total PW Cost Comparison: i = 5%



Total PW Cost Comparison: i = 5%

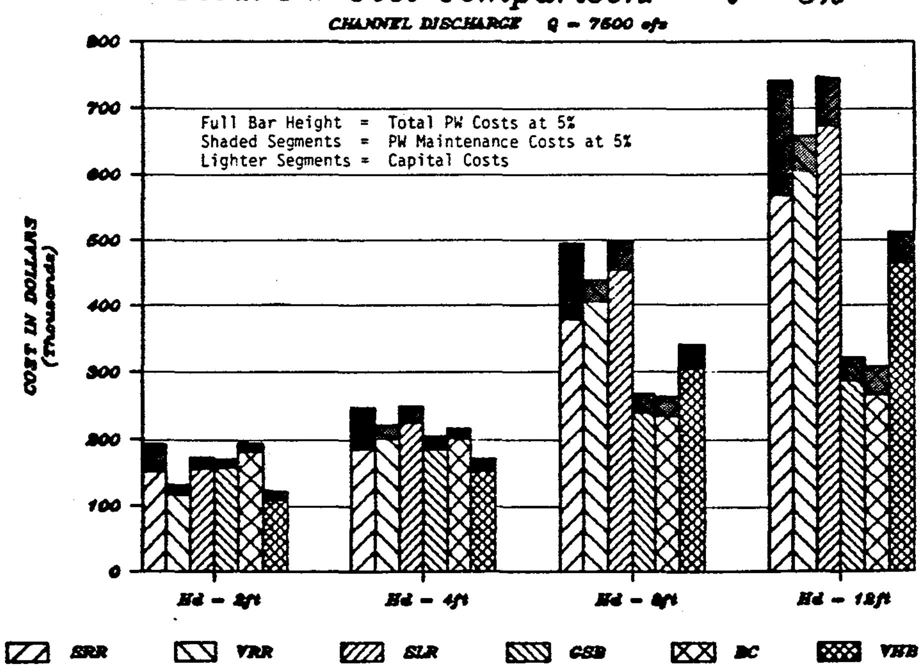
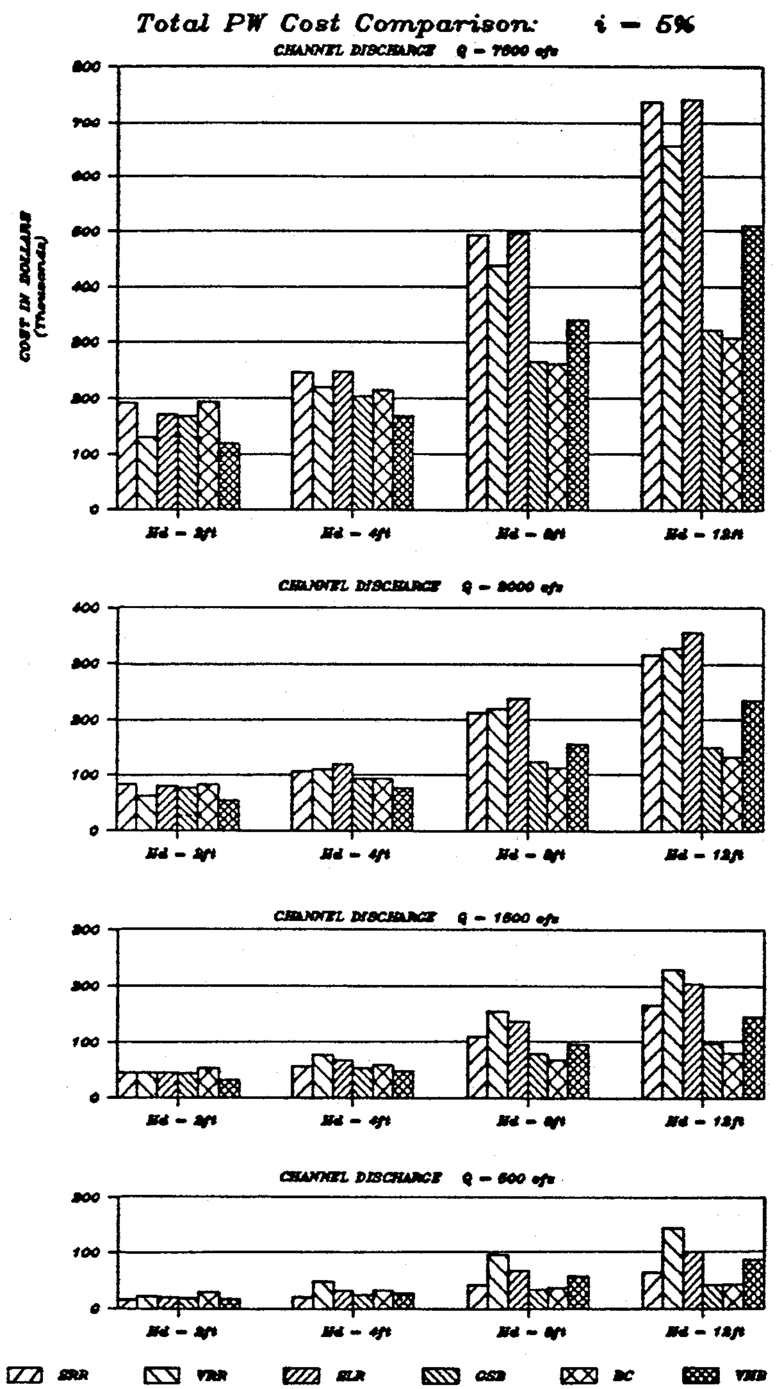


Figure XIII-5



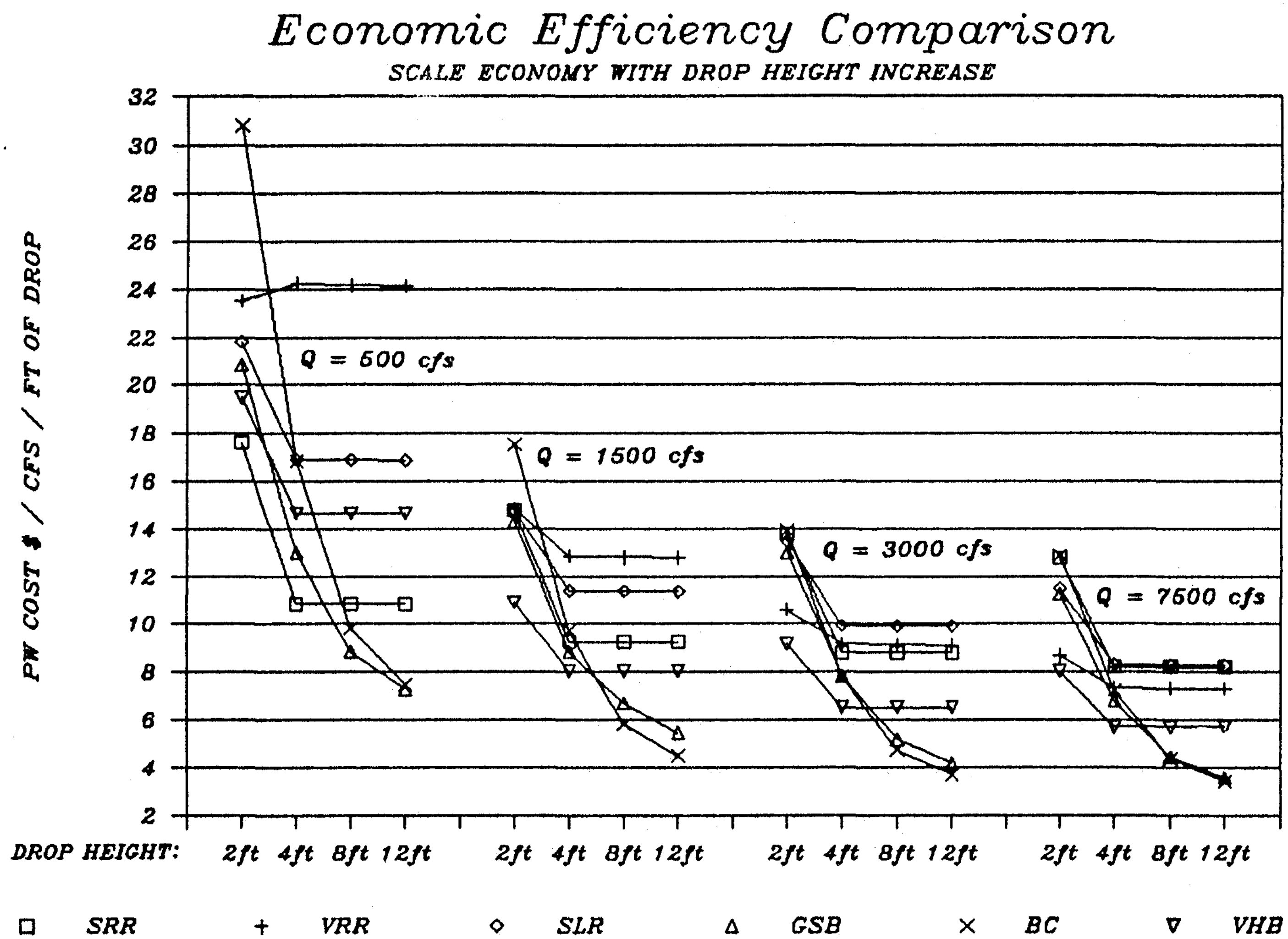


Figure XIII-6

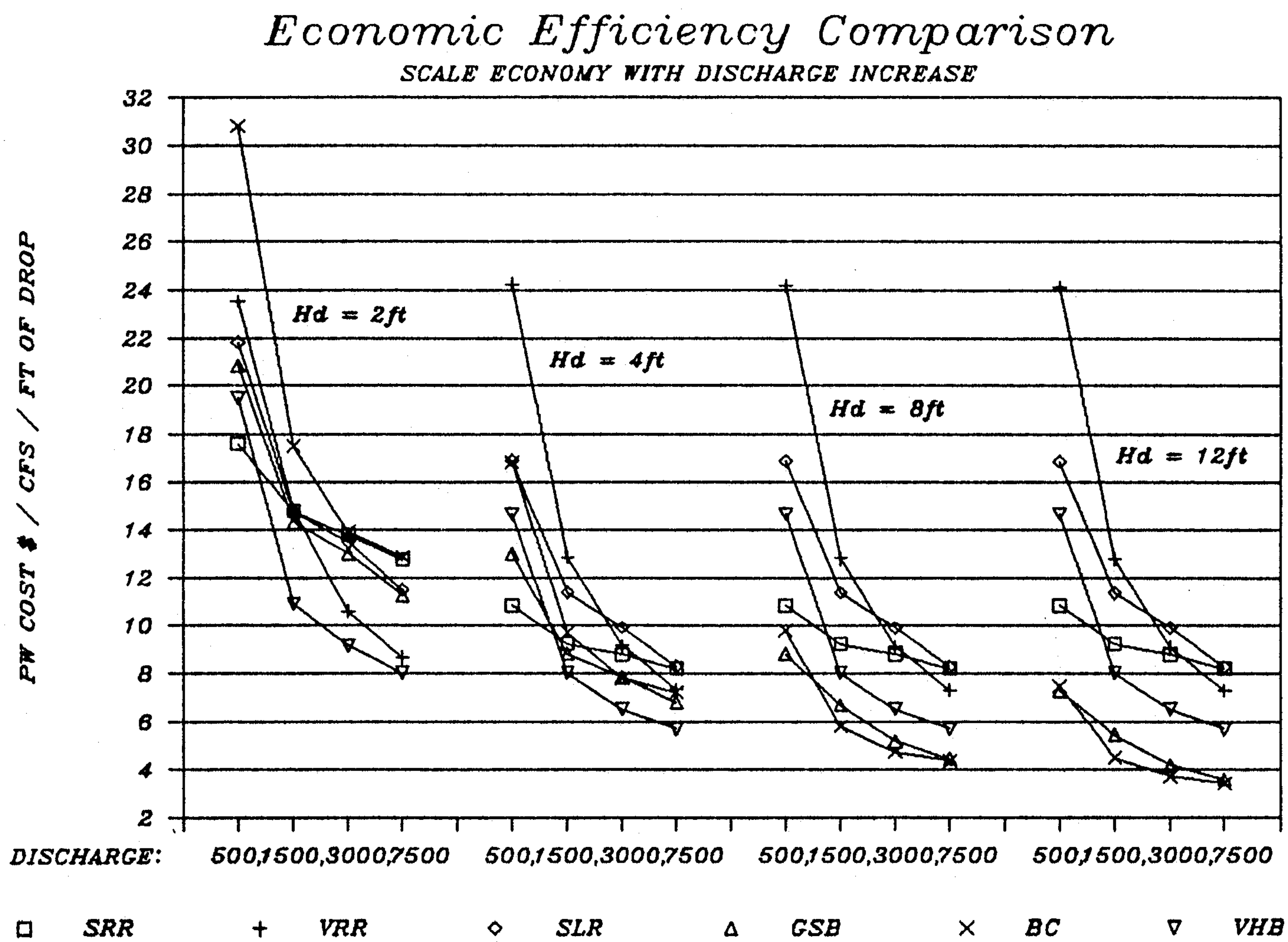


Figure XIII-7

Each group of curves represents a single discharge level. Conversely, Figure VIII-7 displays economic efficiency related to discharge contrasting 5 designs while each group of curves is at a fixed drop height. There are many ways to interpret this information. The graphs provide assistance in interpolating the costs of intermediate configurations. This would involve direct interpolation from either graph or two dimensional interpolation using both graphs. A second application deals with trade off considerations between designs. The cost equivalent cross-over point can be seen for several configurations. This may be valuable information, however, the most interesting results may be interpreted from the trends illustrated.

Scale economy trends are evident in both the drop height and discharge directions. Refering to the first graph (Figure XIII-6), it is apparent that scale economy with increased drop height occurs in every case except one. The SRR design at 500 cfs actually becomes more expensive with increased drop, probably due to high maintenance requirements. Also, it can be seen that the efficiency is level beyond 4 ft. for the designs which have a 4 ft. vertical height restriction. In other words scale economy ceases at 4 ft. for these designs and progresses for the other design. The smallest baffle chute (BC) is very expensive at $31/cfs/ft., whereas the greatest value is realized for the GSB and BC designs (near $3.50/cfs/ft.) at the 12 ft., 7,500 cfs configuration. The general cost relationship trends are important. The slopes of the curves are extremely steep between 2 and 4 ft., then gradually diminish approaching the 12 ft. size. This indicates that a significant savings may be realized by considering a single large drop over constructing a series of smaller structures, when right-of-way and grading permit. Two foot drops are not cost effective relative to the 4 ft. sizes. When the undular jump problems and risk failure are considered, 2 ft. structures appear very undesirable and should be evaluated carefully.

The second graph illustrates continuous scale economies in every case. The 4 ft. vertical drop contraint is seen by the fact that the last three curves (4, 8, 12 ft.) are identical for these designs. Once again, the greatest scale economy occurs in the first increment, although in this case, it is the change from 500 cfs to 1,500 cfs. This indicates that a margin of safety is worthwhile to consider in channel design since the cost relationship is non-linear and has significant economies of scale.

This investigation illustrates that Baffle (Apron) Chute Drops (BC), are the best value. Vertical Hard Basin and Grouted Boulder Drops, as described, are still in somewhat of a developmental phase, although there are many basically successful examples. Further research, testing and design refinements are appropriate so that their inherent value may be realized. Refinements to be explored on these basins include dissipation of jet from the trickle channel area and energy dissipation in low drops and/or shallow tailwater conditions.

In the VHB drop, the use of large boulders as a retaining structure and the actual grout thickness requirements for the grouted rock basin will need monitoring and refinement. There is some potential to derive a combination of these structures, "Stacked Grouted Boulders" which is worth pursuing because of potential cost and aesthetic considerations. The mechanics of flow are different which would require further development and testing. Seepage control would also need to be explored.

Generally, riprap drops have a risk of high maintenance costs, and probably will be more expensive on a capital basis when the design improvements suggested herein are implemented. They appear to be appropriate only for unusual applications by specialists in sediment transport, and then, only after specific site studies. They are not compatible with the time and effort normally available for development projects.

CONCLUSIONS

Economic information is likely to evolve as further experience is obtained. This cost comparison may be used for preliminary screening between alternative drop structure designs which are clearly different in cost. When alternatives considered compare closely using this criteria or are only marginally acceptable even at high discount rates, then a secondary decision criteria should be applied. Valuations may be added to these charts for intangibles such as aesthetics, safety, or ease of construction. Interpretation and application of these results requires some judgement as to the difference between actual site considerations and this idealized model, however, this model is flexible and may be adapted to more precise alternative designs, or different channel conditions. All of these precautions and qualifications are reminiscent of an easily forgotten axiom: It is always easier to assign a cost to something than it is to determine it's value; and value is the ultimate goal in flood control improvements.

SECTION XIV

DESIGN CONSIDERATIONS MATRIX

The following is a spread sheet printout of design considerations that should be helpful in making decisions as to the type of structure to use, analysis steps required, and points that are critical.

The basic classes of drops are as previously designated in this study. The considerations presented are:

Soils and Foundation Precautions
Structures and Foundations
Maintenance Considerations
Hydraulic Phenomena
Suggest Hydraulic Analysis
Hydraulic Analysis Difficulty
Design Hints
Flow and Height Suitability
Construction concerns, including difficulty, materials quality and availability, and suggested quality control measures and inspection.
Aesthetic Problems and Suggestions
Public Acceptability

INDEX TO DESIGN CONSIDERATIONS MATRIX

(The individual sheets may be assembled to provide a display of the entire matrix.)

MAJOR CLASS	SUB CLASS	SOILS AND FOUNDATION CONDITIONS	PRECAUTION	STRUCTURE AND RELATED FOUNDATION CONCERNS	MAINTENANCE DESIGN CONSIDERATIONS AND TYPICAL MAINTENANCE NEEDS
BAFFLE CHUTE		SILTY SOILS	Be especially cautious on piping.	The hydraulic surface loads, such as the forces against the baffle blocks, are given by the USBR. Also typical water surface profiles are given.	Access to the baffle apron for debris removal.
		SANDY SOILS	Be cautious on piping.	The foundation design should consider frost heave and seepage. Especially consider seepage cutoff and any residual pressures that will be against walls or slabs.	Access to the basin.
		CLAYEY SOILS	Normal care.	Sheet pile and other deep cutoff techniques are useful in extreme soils such as sand and silt.	Shaping of the transition area to drain so that maintenance is reduced. This can include a transition from the basin to direct flow into the trickle channel.
		EXPANSIVE SOILS	Be careful of expansive conditions and differential movement.		Consideration of vandal resistant design.
		FREEZE/THAW	Analysis isRequired, particularly at toe but varies for soils conditions		Attention to bank slopes and transition areas, using slopes that are easily maintained with larger mowers, and providing riprap at likely scour areas that are expensive to repair latter.
		SUBDRAINAGE, SEEPAGE	Required, check Lane's Weighted Creep as a minimum and provide sufficient drains, see typical details		
VERTICAL RIPRAP BASIN		SILTY SOILS	Be especially cautious on piping. Seepage cutoff will be difficult and any subsequent piping can cause wall failure. Also take care on bedding and potential excessive scour hole.	The hydraulic and soils loads on the wall are considerable. Be cautious on trying to relieve load by drainage system which might lead to piping.	Access to the area above the crest wall.
		SANDY SOILS	Be cautious on piping and potential scour, but more manageable than above. Sheet pile and clurry cutoffs possible options.	Be sure that structural and geotechnical are aware that rock in basin does rearrange itself and isn't advisable to consider in helping resist wall loads.	Selection and placement of rock above the crest that isn't easily moved by vandals or flow.
		CLAYEY SOILS	Better suited, but bedding and gradation still important.	Potential movement of wall should be considered.	Access to the basin.
		EXPANSIVE SOILS	Better suited, but bedding and gradation still important. Excavate cutoff trench directly into substrate, and place concrete directly into trench (form above grade only).	Consider sheet pile for errosive soils and inherent characteristics of simultaneously reducing seepage and increasing resistance to movement as driven further in the ground.	Shaping of the transition area to drain so that maintenance is reduced.
		FREEZE/THAW	Main concern is durability of rock.		Consideration of vandal resistant design.
		SUBDRAINAGE, SEEPAGE	Required, check Lane's Weighted Creep.		Selection of variables that result in reducing scour basins that trap water. This may include rock size, drop width and trickle channel depth.
					Attention to bank slopes and transition areas, using slopes that are easily maintained with larger mowers, and providing riprap at likely scour areas that are expensive to repair latter.

MAJOR CLASS	SUB CLASS	SOILS AND FOUNDATION CONDITIONS	PRECAUTION	STRUCTURE AND RELATED FOUNDATION CONCERNS	MAINTENANCE DESIGN CONSIDERATIONS AND TYPICAL MAINTENANCE NEEDS
VERTICAL HARD BASIN	CONCRETE BASIN	SILTY SOILS	Be especially cautious on piping.	The structural wall problems are basically the same as with the vertical riprap basins. The basin slab should consider seepage uplift forces and frost action. Gravel drainage and numerous weeps should be provided. Adjacent transition walls and sills should be designed to be compatible, and with due consideration for seepage and frost. Most likely design transition walls with separate footers and joint detail with slab. If sill is small, it can be an extension of slab. Slab joint with main drop wall critical, and to be flexible.	Access to the area above the crest wall. Selection and placement of rock above the crest that isn't easily moved by vandals or flow. grouted rock is desirable. Access to the basin. Shaping of the transition area to drain so that maintenance is reduced, including debris and sediment. A slight downstream vee shape in the lower sill appears helpful. Consideration of vandal resistant design. Attention to bank slopes and transition areas, using slopes that are easily maintained with larger mowers, and providing riprap at likely scour areas that are expensive to repair latter.
		SANDY SOILS	Be cautious on piping. Sheet pile and slurry cutoffs possible options.		
		CLAYEY SOILS	Normal care.		
		EXPANSIVE SOILS	Be careful of expansive conditions and differential movement. Joint between wall and basin slab important.		
		FREEZE/THAW	Consider in design but varies for soil conditions.		
		SUBDRAINAGE, SEEPAGE	Required, check Lane's Weighted Creep as a minimum and provide sufficient drains, see typical details. Design of wall varies as a function of seepage.		
	GROUTED ROCK BASIN	SILTY SOILS	Be especially cautious on piping.	The structural wall problems are basically the same as with the Vertical Riprap Basins. Uplift under the grouted rock basin should be relieved with combination gravel layer and weeps. Check for differential uplift if supercritical flow occurring in basin.	Access to the area above the crest wall. Selection and placement of rock above the crest that isn't easily moved by vandals or flow. Grouted rock is desirable. Access to the basin. Shaping of the transition area to drain so that maintenance is reduced, including debris and sediment. A slight downstream vee shape in the lower sill appears helpful. Consideration of vandal resistant design. Attention to bank slopes and transition areas, using slopes that are easily maintained with larger mowers, and providing riprap at likely scour areas that are expensive to repair latter.
		SANDY SOILS	Be cautious on piping. Sheet pile and slurry cutoffs possible options.		
		CLAYEY SOILS	Normal care.		
		EXPANSIVE SOILS	Be careful of expansive conditions and differential movement.		
		FREEZE/THAW	Consider in design of wall but varies for soils conditions. Design for uplift leads to grout thickness that resists deterioration. Use polyfiber additives and high strength grout.		
		SUBDRAINAGE, SEEPAGE	Required, check Lane's Weighted Creep as a minimum and provide sufficient drains, see typical details. Design of wall varies as a function of seepage. Basin design thickness a function of uplift from tailwater and/or head upstream of crest (and type of wall).		
	SCS with Baffle Blocks in Basin	see above Concrete Basin		See SCS guidelines for detailing. Problems are essentially the same as the Concrete Basin above.	See the above items. Great care should be taken to avoid a sediment and debris trap. If pipes are used they should be in the range of 24 to 36 inch so they can be easily maintained. Trickle channels are preferred over pipes which may plug or frequently overtop, leading to the creation of an unplanned trickle channel and more maintenance problems.

MAJOR CLASS	SUB CLASS	SOILS AND FOUNDATION CONDITIONS	PRECAUTION	STRUCTURE AND RELATED FOUNDATION CONCERNS	MAINTENANCE DESIGN CONSIDERATIONS AND TYPICAL MAINTENANCE NEEDS
SLOPING RIPRAP	GRADED ROCK	SILTY SOILS	Be especially cautious on piping. Seepage cutoff will be difficult and any subsequent piping can cause wall failure. Also take care on bedding and potential excessive scour hole.	The structural is minor for the smaller drops. The crest wall distributes flow and provides somewhat of an insurance policy if some of the rock moves. The reinforcing is mainly to provide integrity, crack control and to allow the wall to stand during construction. When backfill is placed, it is difficult to achieve compaction of the soil along the wall, thus the potential for piping along the wall is high. There are instances where sheet pile or slurry walls are used for erosive soils.	Access to the area above the crest wall. Selection and placement of rock above the crest that isn't easily moved by vandals or flow. Access to the sloping rock and basin. Shaping of the transition area to drain so that maintenance is reduced, including debris and sediment. A slight downstream vee shape in the lower sill appears helpful. Consideration of larger rock and careful attention to providing the larger thickness below the crest. If anything, leave some extra rock that can be used for later maintenance. Attention to bank slopes and transition areas, using slopes that are easily maintained with larger mowers, and providing riprap at likely scour areas that are expensive to repair latter.
		SANDY SOILS	Be cautious on piping and potential scour, but more manageable than above. Sheet pile and slurry cutoffs possible options, besides normal cutoff wall.		
		CLAYEY SOILS	Better suited, but bedding and gradation still important.		
		EXPANSIVE SOILS	Better suited, but bedding and gradation still important. Excavate cutoff trench directly into substrate, and place concrete directly into trench (form above grade only).		
		FREEZE/THAW	Main concern is durability of rock.		
		SUBDRAINAGE, SEEPAGE	Required, check Lane's Weighted Creep.		
	DERRICK STONE per Corps (large boulders over graded riprap)	see above	see above	The derrick stone drop by the SCS/USACE was designed to work with sheet pile, but has application to other structures submerged during flooding. See literature.	see above
	STACKED BOULDERS (Interlocked and stepped)	see above	See discussion above, but one of the key problems is that seepage can quickly develop and lead to abutment failures, subgrade erosion and upstream headcutting. Thus cutoff is paramount. A wide crest (along stream) and location of the cutoff upstream is recommended.	See Discussions above.	see above

MAJOR CLASS	SUB CLASS	SOILS AND FOUNDATION CONDITIONS	PRECAUTION	STRUCTURE AND RELATED FOUNDATION CONCERNS	MAINTENANCE DESIGN CONSIDERATIONS AND TYPICAL MAINTENANCE NEEDS
SLOPING GROUTED ROCK	SINGLE ROCK LAYER	SILTY SOILS	Be especially cautious on piping. Poor grouting leaves voids which lead to erosive underflows and failure. This is especially true in this type of soil, thus inadequate cutoff leads to failure.	The integrity of the cutoff is quite important as seepage and uplift are the key concerns with grout. In most instances the cutoff is relatively simple and requires no intensive structural effort.	Access to the area above the crest.
		SANDY SOILS	Be cautious on piping. Sheet pile and slurry cutoffs are possible options. As with all grouted rock uplift pressure is a critical concern, and certainly this is true with pervious soils.	However, in instances of erosive or highly permeable soils, cutoffs utilizing structures, particulary sheet pile and slurry walls can become necessary.	Access to the sloping drop and basin.
		CLAYEY SOILS	Normal care.	In cases of higher drops, it is particulary important to complete a structural and geotechnical analysis.	Shaping of the transition area to drain so that maintenance is reduced, including debris and sediment. A slight downstream vee shape in the lower sill appears helpful.
		EXPANSIVE SOILS	Be careful of expansive conditions, but mass of grouted rock likely to compensate.		Attention to bank slopes and transition areas, using slopes that are easily maintained with larger mowers, and providing riprap at likely scour areas that are expensive to repair latter.
		FREEZE/THAW	Design for uplift leads to grout thickness that resists deterioration. Use polyfiber additives and high strength grout.		
		SUBDRAINAGE, SEEPAGE	Required, check Lane's Weighted Creep as a minimum and provide sufficient drains, see typical details. Uplift pressures are a key concern in design. Thickness required is a function of uplift from tailwater and/or head upstream of crest.		
	STACKED BOULDERS Interlocked and stepped	see above	see above	see above	see above

MAJOR CLASS	SUB CLASS	SOILS AND FOUNDATION CONDITIONS	PRECAUTION	STRUCTURE AND RELATED FOUNDATION CONCERNS	MAINTENANCE DESIGN CONSIDERATIONS AND TYPICAL MAINTENANCE NEEDS
OTHERS					
SLOPING CONCRETE	SAF Saint Anthony Falls Basin (Sloping Basin with Baffle Blocks in Basin) and Similiar BurRec Basins	SILTY SOILS	Be especially cautious on piping.	The integrity of the cutoff is quite important as seepage, uplift and frost heave are key concerns. Structural analysis is required. There are a wide variety of details and techniques available for handling problems. In instances of erosive or highly permeable soils, cutoffs are critical, with techniques such as sheet pile and slurry walls being useful. In cases of higher drops, it is particulary important to complete a structural and geotechnical analysis.	Access to the area above the crest. Selection and placement of rock above the crest that isn't easily moved by vandals or flow. Grouted rock is desirable. Access to the basin, the drop face and any underdrain maintenance points. Shaping of the transition area to drain so that maintenance is reduced, including debris and sediment. Consideration of vandal resistant design. Attention to bank slopes and transition areas, using slopes that are easily maintained with larger mowers, and providing riprap at likely scour areas that are expensive to repair latter.
		SANDY SOILS	Be cautious on piping.		
		CLAYEY SOILS	Normal Care.		
		EXPANSIVE SOILS	Be careful of expansive conditions and differential movement.		
		FREEZE/THAW	Required, particularly at toe and sloping face, but varies for soils conditions.		
		SUBDRAINAGE, SEEPAGE	Required, check Lane's Weighted Creep as a minimum and provide sufficient drains.		
	Conventional	see above		Essentially the same	Great care should be taken to avoid a sediment and debris trap. If pipes are used they should be in the range of 24 to 36 inch so they can be easily maintained. Trickle channels are preferred over pipes which may plug or frequently overtop, leading to the creation of an unplanned trickle channel and more maintenance problems. Access for basin area is especially important.
SOIL CEMENT, ROLLERCRETE		SILTY SOILS	Be especially cautious on piping.	The critical concern is seepage. This is a massive structure and unlikely to have sliding or rotation problems.	see above Great Care should be taken to avoid a sediment and debris trap. If pipes are used they should be in the range of 24 to 36 inch so they can be easily maintained. Trickle channels are preferred over pipes which may plug or frequently overtop, leading to the creation of an unplanned trickle channel and more maintenance problems.
		SANDY SOILS	Be cautious on piping. Compatible situation, but depends on materials and economics of other alternatives.		
		CLAYEY SOILS	Depends on economics of other alternatives (or lack thereof).		
		EXPANSIVE SOILS	Be careful of Expansive conditions and differential movement. Unlikely to make sense because insitu shales resist erosion and easily protected by other options (concrete, rock, grout).		
		FREEZE/THAW	Critical to prepare laboratory tests to determine suitability of materials and cement content.		
		SUBDRAINAGE, SEEPAGE	Required, check Lane's Weighted Creep as a minimum.		

MAJOR CLASS	SUB CLASS	BASIC HYDRAULIC PHENOMENA	SUGGESTED HYDRAULIC ANALYSIS	HYDRAULIC ANALYSIS DIFFICULTY	OTHER DESIGN HINTS
BAFFLE CHUTE	-------------------	Water flow is obstructed by 4 rows of staggered blocks that are of a nominal height equal to critical depth. Energy is dissipated by significant loss of momentum and related turbulence. Large amount of flexibility for varying tailwaters, bed conditions, excess flow. Only serious liability is that excessive debris can plug and allow supercritical flow over blocks directly to channel downstream.	CREST CONTROL HYDRAULICS TRANSITION HYDRAULICS UPSTREAM (approach velocities need careful consideration) CHUTE LAYOUT/HYDRAULICS per BurRec TRICKLE CHANNEL AT CREST (provide by going between blocks) TRANSITION HYDRAULICS DOWNSTREAM (confirm reasonable dispersion	-OK -Reasonable, but unusual situations occur. -Easy -Sometimes difficult with wider grass channel.	Locate and configure trickle channel at crest to go thru crest between two baffles. Use concrete transition from trickle upstream to prevent debris and silting, and also to help with seepage control. It is possible to apply the design to low drops by flattening slope to allow 4 rows of baffles, or using only 3 rows. Also, in the case of completly stable channels the downstream basin can be hard lined to allow a cleaner transition. This is done by bringing a trickle channel upstream to the drop and creating a depressed basin equal to approximately half the trickle depth. The basin should then have cross slope to drain to the trickle. It should have a base width equal to the channel and long enough to provide about a 15 to 25 degree expansion.
VERTICAL RIPRAP BASIN	-------------------	Flow over crest falls into pool where energy of jet (nappe) is dissipated in pool by turbulence. The basin is depressed, typically because of a rearranging of the rock associated with the turbulence. Model and field observations have lead to development of empirical Charts. Sucessful results are obtained As long as field conditions and flow hydraulics don't exceed the limitations.	CREST CONTROL HYDRAULICS TRANSITION HYDRAULICS UPSTREAM BASIN LAYOUT/HYDRAULICS per EMPIRICAL CHARTS TRICKLE CHANNEL AT CREST TRANSITION HYDRAULICS DOWNSTREAM (confirm reasonable dispersion of flow to channel) TAILWATER HYDRAULICS (Backwater Analysis)	-OK -Reasonable, but unusual situations occur -OK -Need to consider -Sometimes difficult with wider grass channel and problems with secondary drop formed by basin rock rearrangement. -Sometimes difficult, especially if changing bed conditions.	Bring trickle channel through crest and size large rock in basin below. Bring trickle channel from downstream into basin as low as possible to drain basin, but have adjacent channel bottom in grass lined channel form sill effect. In other words, the basin elevation will rise to the elevation of the downstream channel base except at the trickle channel. Having heavy clay content in the backfill for the wall and in the channel bottom upstream can provide an important flow cutoff. Alternatively one can use synthetic liners to reduce seepage. Drops have been seen where the trickle flow is going behind the wall thru the drains, and not over the crest. Differential settlement, where the trickle settles upstream of the crest, should be handled by structural details and setting grades that anticipate movement.

MAJOR CLASS	SUB CLASS	BASIC HYDRAULIC PHENOMENA	SUGGESTED HYDRAULIC ANALYSIS	HYDRAULIC ANALYSIS DIFFICULTY	OTHER DESIGN HINTS
VERTICAL HARD BASIN	CONCRETE BASIN	Flow over crest falls into a pool where the jet (nappe) hits the basin floor and then energy is dissipated by the turbulent flow of the hydraulic jump. Model and field observations have lead to development of empirical charts. Sucessful results are obtained As long as field conditions and flow hydraulics don't exceed the limitations. Parameters relate to a Drop Number (See Section XII). If tailwater is insufficient super-critical flow will travel downstream until sufficicent energy has been dissipated and then the jump will occur.	CREST CONTROL HYDRAULICS TRANSITION HYDRAULICS UPSTREAM BASIN LAYOUT/HYDRAULICS per EMPIRICAL CHARTS TRICKLE CHANNEL AT CREST TRANSITION HYDRAULICS DOWNSTREAM (confirm reasonable dispersion of flow to channel) TAILWATER HYDRAULICS (Backwater Analysis)	-OK -Reasonable, but unusual situations occur -Easy -Need to consider -Sometimes difficult with wider grass channel and problems with secondary drop formed by basin rock. -Sometimes difficult, especially if changing bed conditions.	The provision of a substantial gravel layer, good weeps and good detailing on joints will add to the life of the structure. Keep in mind that the slab is relatively thin and has little ballast against uplift, in contrast to grouted rock basins. Use a 2 foot depth trickle channel that transitions to allow approximately 1 foot of depth to be used for the basin depression. The drop wall should have a trickle channel of the same depth (2 feet). The basin should have cross slope to allow it to drain to the trickle channel.
	GROUTED ROCK BASIN	See Above	See Above	See Above	In this case, probably use a gravel layer under the grouted boulders and weeps. Consider potential uplift in sizing the grout layer. The controlling uplift can be caused either by the differential head from upstream after considering seepage losses, or by local effects caused by differential water surfaces for supercritical and subcritical flow conditions. The rough surface of the grouted rock helps to dissipate energy, thus hold the grout below the top of the rock. Grade the grout to encourage surface drainage. If the supercritical flow is tending to wash out of the basin, place larger boulders that project into the flow. The area of the trickle channel is of key concern. Meandering the trickle in the basin may also help. Place any boulders at least 20 feet upstream of sill to allow eddies to dissipate. Use a 2 foot depth trickle channel that transitions to allow approximately 1 foot of that to be used for the basin depression. The crest wall should have a trickle channel of the same depth (2 feet). Consider forming basin side walls of large boulders, carefully bedded on riprap and placed to minimize voids. Many other creative treatments/components are possible.
	SCS with Baffle Blocks in Basin	Similiar to above	SEE SCS DESIGN GUIDELINES -Implementation of Trickle Channel needs to be analyzed. -Drainage Analysis of Stilling Basin, and related piping needs to be undertaken unless wet basin acceptable.	Method somewhat intricate, and requires deep basin that is usually can't be drained by the trickle channel. -No guidelines available but reasonable to approximate. -Difficult to design a reliable system unless large conduits used.	As for concrete basins above. An important concern is drainage of the stilling basin. Don't use small pipes or other details subject to silting or plugging.

MAJOR CLASS	SUB CLASS	BASIC HYDRAULIC PHENOMENA	SUGGESTED HYDRAULIC ANALYSIS	HYDRAULIC ANALYSIS DIFFICULTY	OTHER DESIGN HINTS
SLOPING RIPRAP	GRADED ROCK	Basic Energy Dissipation is accomplished by conventional hydraulic jump and turbulent flow over (and through) rock. The flow through the rock can create highly varying instantaneous pressure fluctuations associatted with impact, lift and drag. At best, empirical parameters usually based on much smaller scale model tests are used to size rock.	CREST CONTROL HYDRAULICS	-OK	A good idea for cutoff wall construction is to excavate a trench below rock subgrade as required for seepage control, and backfill with concrete. Above this grade a formed surface can be used. Often a wall with almost no footer is constructed, and then backfilled. This method is poor because compaction and associated seepage control is difficult.
			TRANSITION HYDRAULICS UPSTREAM	-Reasonable, but unusual situations occur	
			BASIN LAYOUT/HYDRAULICS per SIMPLIFIED CHARTS, or	-Reasonably easy to use, but almost equally easy to misapply such as incorrect tailwater assumptions and effects of tailwater, incorrect discharges, incorrect assumptions about contractions, and locations on curves.	
			COMPLICATED SERIES OF ANALYSES INCLUDING: -Supercritical water surface profile analysis down slope and in basin. -Determination of beginning of jump. -Analysis and sizing of rock.	-Certainly the quality of the Analysis and the reliablity of the design is much better, but the level of effort is much more extensive, and incorrect parameters are easily assumed.	It would be preferable in sandy, or other marginal soils where a narrow trench cannot be excavated, to completely overexcavate a wide zone and backfill with tight clay using heavy earthwork equipment. Then the trench could be excavated as above.
			TRICKLE CHANNEL AT CREST SIMILIAR ANALYSIS FOR HYDRAULIC AND ROCK SIZING ANALYSES IN TRICKLE CHANNEL.	-Need to consider, which then leads to two complete series of analyses, one for the main drop and the other for the trickle channel.	Use a 2 foot minimum depth trickle channel that transitions to allow approximately 1 foot of that to be used for the basin depression. The drop wall should have a trickle channel of the same depth (2 feet).
			TRANSITION HYDRAULICS DOWNSTREAM (confirm reasonable dispersion of flow to channel)	-Any rock smaller than d50 is likely to move and will form secondary drops and local erosion. This compounds the problems associated with the transition downstream. With varying bed conditions the analysis is even more complex.	
			See discussion for Derrick Stone and stacked boulders when analysis indicates extremely large rock.		
	DERRICK STONE per Corps (large boulders over graded riprap)	The SCS/USACE Technique apparently sets up a submerged hydraulic jump on the face of the drop.			
		-The same rock gradation technique can be applied when rock sizing algorithms indicate very large rock for conventional drops as in graded riprap drops above.	-See discussion above for Graded Rock.		
	STACKED BOULDERS (Interlocked and stepped)	The phenomena here is somewhere between a sloping drop with a conventional jump and a plunging jet falling into a basin below. There is no literature available which investigates the phenomena taking place. We hypothesize that the boulders are large relative to the surface flow so that under flow circulation is reduced such that lift forces are insignificant, and thus the general stability experienced.	-Review the drop utilizing several techniques. -Once it is indicated by all that the rock size is two or three times the supercritical flow depth, consider stacking and interlocking the rock such that each upstream rock is 50% below the top of the downstream rock, with all adjoining sides contacting as close as possible. -Bedding and seepage analysis is Critical.	See above. -Difficult to do and basically involves a lot of guesswork, and experience. The best thing to do after analysis is to assess risks with the client and if still perceived as a desirable solution because of reasons such as aesthetics; low discharge ranges; suitability for erosion check structures, or low drops; then proceed but be prepared for corrective work.	

MAJOR CLASS	SUB CLASS	BASIC HYDRAULIC PHENOMENA	SUGGESTED HYDRAULIC ANALYSIS	HYDRAULIC ANALYSIS DIFFICULTY	OTHER DESIGN HINTS
SLOPING GROUTED ROCK	SINGLE ROCK LAYER	Basic Energy Dissipation is accomplished by conventional hydraulic jump and turbulent flow over rock.	CREST CONTROL HYDRAULICS TRANSITION HYDRAULICS UPSTREAM BASIN LAYOUT/HYDRAULICS per SIMPLIFIED CHARTS, or	-OK -Reasonable, but unusual situations can occur -Reasonably easy to use, caution is appropriate regarding controlling seepage conditions, such as flow (and thus pressure) conditions at drains, crest and in or downstream of basin. But it appears that correct knowledge of depths upstream and downstream leads to a correct thickness, assuming correct seepage characteristics (Lane's Weighted Creep Length per soils).	The best cutoff techniques involve moving upstream of the actual crest, where it is easier to physically excavate a trench to be backfilled with concrete as described above for sloping riprap. The cutoff can realistically be located 5 to 20 feet upstrem, with a grouted rock surface layer to seal the cutoff and provide erosion protection. Be sure to provide toe drainage. Do not use gravel under grout as it only provides a piping route and transmits pressure to other locations.
			SERIES OF ANALYSES INCLUDING: -Supercritical water surface profile analysis down slope and in basin. -Determination of beginning of jump. -Sizing of grout thickness as a function of hydraulics and seepage forces.	-The quality of the analysis and the reliablity of the design is much better, but the level of effort is much more extensive.	The keys to successful grout work are to prepare a solid subgrade; use boulders larger in all dimensions than the grout layer; place the boulders to minimize voids and step gradually so that at least the bottom half of the uphill boulder is behind the adjoining one; generally place the boulders with the top surface flat and horizontal to provide a stepped appearance conducive to flow dispersal and minimization of projecting surfaces that might develop lift (although not usually a problem); pump the grout with modest slump depending on slope; use polyfiber reinforcement for crack control and general toughness; use a pencil vibrator to make sure it penetrates under to prevent piping through voids and to smooth the surface; and hold the grout down.
			TRICKLE CHANNEL AT CREST SIMILIAR ANALYSIS FOR HYDRAULIC AND ROCK SIZING ANALYSES IN TRICKLE CHANNEL.	-Need to consider, which then leads to two complete series of analysis, one for the main drop and the other for the trickle channel. Use of simplified design charts usually is voided immediately by significant contractions or varying tailwater conditions, or significant changes in upstream and downstream nominal channel depths.	The best way to help dissipate energy will be to keep the grout below the surface of the boulders in order to create a high realitive roughness. Use larger boulders that project into the flow to prevent erosion and the jump washing downstream. Place boulders at least 15 to 20 feet upstream of sill. Grade the grout to encourage surface drainage.
			TRANSITION HYDRAULICS DOWNSTREAM (confirm reasonable dispersion of flow to channel)	-With varying bed conditions the analysis is even more complex.	Use a 2 foot minimum depth trickle channel that transitions to allow approximately 1 foot of that to be used for the basin depression.
	STACKED BOULDERS Interlocked and stepped	The phenomena here is somewhere between a sloping drop with a conventional jump and a plunging jet into a hard basin below.	See above	See Above	See Above, but keep in mind that cutoff may have to be further upstream from the crest boulders.

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APPENDIX A

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utilizing a probabilistic/stochastic approach as suggested by Samad (ref. 43) and incorporation of a safety factor concept as outlined by Stevens (ref. 60). The probabilistic method will enable the designer to interpret the stability of riprap by indicating its probability of adequacy. Undoubtedly, this would involve basic research on temporal and spatial pressure fluctuations imparted on rock, similar to the work by Urbonas (ref. 64), but more directly applicable to drops, banks, transitions and channel linings. Ultimately, nomographs similar to those by Reese would be useful (ref. 37). They should also incorporate the efforts of Bathurst (ref. 4) regarding roughness and flow characteristics when relative flow depths are smaller as they often are in transitions, steeper slopes or drops. Also, such an investigation should review the rock placement concept discussed herein versus single layer graded riprap concepts.

A useful diagram is Shield's Diagram for studying incipient motion of small particles on flat bed channels. This diagram or a similar diagram needs to be systematically developed for steep channel by including the variables that significantly affect the motion of large particles.

55. Another important general research topic is the interplay between drop crest, trickle channel and overall channel stability. The concern recognized herein is that lack of a trickle channel results in aggradation upstream, along with the effect of extremely wide channels with relatively shallow flows. The investigation here would be conducted based on both laboratory and field research. As part of this study, recommendations were made purely on the basis of experience and field inspection. The loss of 2 feet of conveyance or the degradation of several feet, in projects that cost millions to implement in and of itself justifies research, not including the future projects and problems.

This study should incorporate research on trickle channel and other stability measures in and their effect on natural channels.

boulder side wall in the VHB basin to determine the adequacy of the design in the highly turbulent area near the point where the nappe drops into the basin and other eddy zones. Two (VHB, GSB) of the three preferred drops have clear economic advantages. However, they are predicated on the experience of engineers who have been working and developing the design over a number of years, and basic research that indicates the concept should be effective (ref. 4, 24, 25). To immediately embark on a wholesale shift to these designs, where engineers are not familiar with the problems, without pursuing a parallel track of research and technology transfer, is not recommended and will result in many more dollars spent on maintenance than on research costs.

52. As a parallel effort to item 51, probably using the same model, stacked boulders and grouted stacked boulder drops should be explored. The aspects that should be investigated are: equivalent crest control hydraulics, approach drawdown curves, velocity patterns, flow hydraulics over the drop, impact forces on the basin and basin/jump hydraulics. The work by Bathurst (ref. 4) would indicate positive results, but the scale of the boulders are larger and the slopes/steps are face steeper which leads to the need for research. The promise here is a more economical drop, but there is almost nothing in the literature that applies. Seepage control aspects would be investigated at the same time by exploring upstream cutoffs with a crest cap that extends down to the crest of the drop.

53. As part of all of the above efforts, and in some prototype structures, pressures of the flow above and under the grouted rock drops should be monitored. Comparison with Lanes Weighted Creep Method should be made to suggest modifications unique to the configurations used herein.

54. An important general research area is riprap. The exact formulation of what should be done here is dependent on decisions regarding the continued general use of riprap for drop structures, and the perceived adequacy of general bank and channel riprap. At a minimum, it is suggested that the safety factor/slope correction approach be implemented District wide, with special consideration for transitions and banks. The basis of the safety factor would be a developed

C presents quantity data so that the engineer can consider effects of specific unit prices. The figures in Section XIII should be useful.

DESIGN CONSIDERATIONS MATRIX

49. Section XIV presents a "decision" matrix which allows review of the key considerations related to many types of drops. These include:

- i) Soil and Foundation, Precautions
- ii) Structures and Foundations
- iii) Hydraulic Phenomena
- iv) Suggested Hydraulic Analysis
- v) Hydraulic Analysis Difficulty
- vi) Design Hints
- vii) Flow and Drop Height Suitability
- viii) Construction concerns, including difficulty, materials quality and availability, and suggested quality control measures and inspection.
- ix) Aesthetic Problems and Suggestions
- x) Public Acceptability

RESEARCH NEEDS

50. There are important improvements which can be made that will result in better economy and quality. For the following recommendations, the potential return on investment is high. Also, it would be reasonable to participate in joint venture investigations as these topics have regional and national significance.

51. The first research topic might be titled, "Hydraulic jump stability and dissipation of residual energy in low drops for grass-lined and erodible channels". The study would be concerned with the effects of, advantages of, and guidelines for rock stilling basins with large boulders used selectively for baffles (for jet dispersal and energy dispersion). The differences in the flow through the trickle channel and main jump with basic flow dispersal (velocity patterns) should be investigated and then modifications, such as the boulder baffles, would be investigated. Scour patterns downstream and erosion control measures would be investigated. Another aspect that would be reviewed is the stacked

are discussed in the Design Guidelines. Further research, testing and monitoring is advisable.

OTHER COMMENTS ON ROCK RIPRAP

40. It is apparent that there are many problems in analysis, design, specification, construction and maintenance of riprap. These extend beyond the sloping rock drops and affect "ordinary" bank and channel riprap. There are reasons to also consider safety factors, effects at bends and transitions and probabilistic/stochastic analyses to assign meaning to safety factors.

41. There is disagreement on grading and bedding techniques. The District should monitor candidate projects to identify the better approaches. The gradation tests performed for the City of Englewood during this project illustrate that "eyeball" methods are unreliable, and that periodic testing during a project is warranted. The opinion herein is that placement which ends up with the d_{50} pieces on the surface, interlocked, voids filled with smaller pieces that are trapped and the mass well compacted are likely to be effective and enforceable in the field. The remaining portions of the riprap are in effect to provide a reverse filter and subgrade leveling course on top of a well matched bedding filter layer. On the other hand, placement consisting of large rock strewn about with large voids and exposure is an invitation to disaster.

42. Related suggestions are incorporated in a guide construction specification (Appendix B).

ECONOMICS/COST CONSIDERATIONS

47. Section XIII presents a detailed evaluation of capital and maintenance costs. Various interest rates are compared, along with suboptions for some alternative designs.

48. An economic "efficiency" term is derived, which is useful in demonstrating economy of scale of the drop types. Designers may use this information for initial screening and alternative selection within the limitations noted. Appendix

LOW FLOW EROSION CHECKS AND CONTROL MEASURES

33. Flood plain management practices have resulted in the preservation of the flood plain and natural channels. However, the impacts of urbanization have been significant as the increased runoff volumes that continually flow cause degradation of the low flow channel and bank sloughing. In many cases, this has lead to major damage to the main channel and endangered property, utilities and structures.

34. Checks and other control measures are effective techniques as discussed in Section VIII. Great care needs to be taken with seepage control and good hydraulic performance.

35. These improvements will require maintenance, which can be reduced by careful design, but cannot be reasonably avoided.

36. An important aspect is to have these improvements implemented by development, or by special districts/local governments that can responsibly fund these improvements. Once the channel is initially stabilized, it is reasonable for the District to consider maintenance involvement.

TRICKLE CHANNELS

37. Provisions for trickle channels through the drop structures is important to avoid channel aggradation upstream and to allow a depressed basin for better energy dissipation. Such depressed basins can also drain, and accumulates less debris and sediment because of the trickle channel. Significant aggradation has occurred in many channels where trickle channels do not pass unipeded through the crest.

38. Their inclusion requires hydraulic analysis of two profiles, one through the main drop and one through the drop along the trickle channel. The basics are discussed in Section X.

39. The jump through the trickle channel inherently has more power and tendency to wash downstream. This appears reasonable to control, and initial approaches

27. Placing boulders in a stepped pattern is attractive. There is no functional need to grout to the surface of the boulders. In fact, holding the grout 6 to 9 inches (or more if the minimum thickness is provided) below allows greater hydraulic roughness and improved aesthetics.

28. Construction of this drop is more reasonable than SLR drops, more troublesome than BC drops and comparable to VHB drops.

29. Research, similar to that suggested in 9.i) is appropriate. The items of importance are the jump characteristics in the trickle channel area, the suggested measures of meandering in the trickle channel in the basin, and the use of large boulders as baffles to dissipate the jet.

Sloping Concrete

30. USBR IV and SAF basins, both with baffles on the basin floor may be considered, but the depressed basin is a nuisance in a grass-lined channel. BC drops are generally better for grass-lined and erosive soils.

31. Smooth Concrete Aprons (USBR I, V) are appropriate for hydraulic dissipation such as when dropping into ponds. However, they are a significant hazard because the hydraulic jump is difficult to escape (if a person inadvertently is swept into the basin, etc., or kids are tubing on the smooth face) and laymen (and even many engineers judging by the casualties) do not perceive or recognize the hazard.

Other Types of Drop Construction

32. Soil Cement (ref 49, 51), Rollercrete (ref. 39), and drops along supercritical or steep channels (ref. 40, 41, 49, 51) have been addressed to a lesser degree in this report, as they are not normally applied to grass-lined channels in the Metropolitan area. There are circumstances where these concepts may apply such as a readily available material source (soil cement), while other material are not readily or economically available, or the need to modify an existing concrete dam.

20. The stacked boulder drops and "Derrick Stone" approaches have merit, because both have been successful. Techniques used for rock installation are worth considering. Research should be undertaken in conjunction with Item 11.

Grouted Sloping Boulder Drops - GSB

21. There are many successful examples of these drops. The District has had success in maintenance projects that used grout to stabilized failed loose riprap drops. On the other hand, the Corps of Engineers (COE) and Dr. Simons have noted many failures associated with seepage and uplift.

22. This drop, along with Baffle Apron Drops (BC) and Vertical Hard Basins (VHB), have the most value. GSB drops have economic advantages in several applications, including drops 4 foot and higher. Also, they should be a good approach for drainage inflows to channels (if the water is directed into the chute and seepage is controlled).

23. Section XI reviews the forces and problems involved. Seepage must be controlled by constructing a vertical cutoff upstream of the crest to conservative values for the specific site conditions. Approaches are discussed which are different than SLR drops, as the need for seepage control is more important and requires more extensive work.

24. Regular riprap absolutely should not be used with grout. Rock with all dimensions greater than the grout thickness should be required and placed on a firm subgrade. Grout should be placed with a low pressure grout pump and small vibrators such that the voids to subgrade (below the designated surface grout line) are filled. Generally, no bedding is required.

25. A large trench toe drain across the drop is required. For large vertical or flat slopes, analysis may require other lateral drain trenches on the face.

26. The force analysis requires hydraulic profile analysis because the critical uplift forces are inherently a function of this profile.

problem are improving, but there are still many aspects that are only qualitatively understood.

15. Considering the numerous failures, and the difficulty of analysis, it is recommended that sloping riprap drops not be used as a standard approach. This is particularly true for the development community which generally cannot afford the analysis time and the quality control effort.

16. There may be instances where this type of drop is acceptable. In such cases, a thorough analysis should be conducted, using the information contained herein as a minimum standard (see Section X, Equation X.9 and Figures X.14 through X.17).

17. The Owner should be appraised of the probabilistic nature of the problem. The question is not will the rock move, the question is, how much and with what frequency the rock will move. The Owner is taking this risk unless the designer takes it for him. The District is advised that it is not reasonable for it to assume maintenance responsibility of riprap unless the basic risk is reduced by using a 1.5 safety factor in design and construction practices are improved.

18. If there is a strong insistence that this type of drop be continued, then probabilistic and stochastic approaches should be developed for this particular problem along the lines taken by Samad (ref. 4). Further basic research may be necessary to support selected design standards. The point is to be able to interpret what a given safety factor means in terms of probability for example it could be stated that during a 100-year flood a certain amount and size of rock may move. For the interim, a 1.5 safety factor has been assigned as suggested by many.

19. The vertical crest wall is of critical importance and should be considered with the inclusion of a trickle channel. Vertical crest walls have saved numerous projects from total failure. Practices to improve seepage control are suggested, including filling an excavated trench with concrete and forming the wall only above the rock subgrade. Seepage control is poor in fill along vertical walls.

further. The flow in the basin area will be highly turbulent, and may pose more problems than anticipated. The stacked boulder drops which were investigated have not experienced many problems with stability, but this situation may be different. Concrete side walls may prove more desirable, and should not add greatly to the total costs.

10. Safety is a concern since the vertical crest wall cannot be fenced due to hydraulic considerations. Signage and control fencing to discourage access to the vertical wall is recommended. Owners should be appraised of this risk factor.

11. For small drop-heights it appears worthwhile to explore grouted stacked boulders for the crest wall. Research regarding these drops is suggested. A demonstration program, following the research phase would be helpful to refine and develop guidance. The potential exists to realize further economy for low drops while providing an aesthetic design.

Sloping Rock Drops

12. Construction problems related to riprap for sloping rock drops are nearly overwhelming. The present guidelines should be discontinued because of the low safety factor. The design was based on the concept that the rock would rearrange and largely stabilize except for more severe events. This rearrangement has been observed and is a significant problem in grass-lined channels.

13. Actual flow depth, energy gradient, drop slope (including its effect on safety factor) and angle of repose of the rock utilized are all factors which need to be considered. Improvements in these areas are suggested and sizing guidelines are presented. They are based on a literature search and an approach which combines the investigation of several researchers. The approach is also supported reasonably well by case studies in Denver completed as a part of this work.

14. Flow over sloping rock is complex, and makes design considerably more difficult than any other type of drop. One only has to review Section X and Appendix D to begin understanding the complexities. The tools to deal with the analysis

5. Riprap quality control and subgrade protection (bedding) are of concern.

6. This design is based upon the planned rearrangement of the riprap by the flow of water, which forms a mound of riprap near the end of the basin. This forms a secondary drop that at other flows may cause some problems with grass-lined channels. Grading and trickle channel design downstream should take this into consideration. Installations should be monitored to provide future guidance in this area.

Vertical Hard Basin Drops - VHB

7. There are numerous examples of this type of drop (VHB) in the field. For various reasons, a large number of configurations and materials have been used. This investigation suggests that the retaining wall be reinforced concrete or sheet pile depending on geotechnical/seepage considerations. The basin may be reinforced concrete, but it appears that grouted rock with sidewalls of stacked boulders has advantages of hydraulic performance and economy.

8. The VHB drop appears to be the most economical for low drop heights. However, all small drops (where critical depth is greater than drop height - see Section X) have problems with the persistence of potentially erosive jets and waves.

9. There are a few aspects requiring ongoing monitoring which will likely lead to future standard refinements. These include:

   i) Review of the jump stability and measures taken to dissipate energy (waves and jets in the trickle channel area), particularly the rough surface of the grouted rock basin and the suggested use of meanders and boulders in the trickle channel. The performance of boulders which are placed to project above the basin into the flow path to act much like baffles should be investigated. Experience and literature (ref. 4) supports this as an effective dissipation mechanism.

   ii) The suggestion that basin side walls should be made of stacked large boulders (with riprap and conventional bedding layers) needs to be explored

SECTION XV

CONCLUSIONS, COURSE CORRECTIONS AND RESEARCH NEEDS

DROP STRUCTURES

Baffle (Apron) Chute Drops - BC

1. BC Drops have performed very well and have probably the best long-term value. Although there are many instances where Vertical Hard Basin (VHB) and Grouted Sloping Boulders (GSB) are more economical, they are subject to more refinements (analysis, design and maintenance) in the future.

2. BC Drops are the easiest to design, practically the easiest to build with conventional construction techniques, and the most reasonable in quality control efforts.

3. BC Drops are probably the most hydraulically compatible with grass-lined channels (or other channels with low tailwater conditions), that can function well for a large variation in tailwater (high to low), the only drop that is effective for varying bed conditions without construction of a massive buried basin and one that can be fairly easily modified for radical changes in bed conditions.

Vertical Riprap Drops - VRR

4. It is apparent that Vertical Riprap Drops are feasible, although there is not an extensive number of structures in the Metropolitan area. It is suspected that the reason for the small number is the structural requirements for a retaining wall that has to be constructed to a greater depth to consider the anticipated basin rock movement and seepage measures provide difficulties.

MAJOR CLASS	SUB CLASS	AESTHETIC PROBLEMS AND SUGGESTIONS	PUBLIC ACCEPTABILITY
OTHERS			
SLOPING CONCRETE	SAF Saint Anthony Falls Basin (Sloping Basin with Baffle Blocks in Basin) and Similiar BurRec Basins	Sloping Concrete Basins are very bleak because of the large areas of Concrete exposed to view. Color additives and exposed aggreagate can mitigate, but little can be done. Some designs have bypassed low flows and put sod in the basin with the intent that a major flood will wash the sod out. Generally they are to be avoided. The stilling basin can be used as a pool, but can become a debris and sediment laden basin.	Generally, the acceptability is not good. These structures would be a barrier to fish passage, and are not well liked by the environmental community. Safety is of concern because the hydraulic jump is a trap for anyone that might try to float through the drop (even when playing in low flows as children will do) or for a person swept into the drop. The provision of signs is advisable.
	Conventional		
SOIL CEMENT, ROLLERCRETE		Soil Cement and Rollercrete would generally fall in the category of Sloping Concrete Drops, subject to further mitiagation such as surface treatments which tend to have a little more variety.	Generally, the acceptability is not good. These structures would be a barrier to fish passage, and are not well liked by the environmental community. Safety is of concern because the hydraulic jump is a trap for anyone that might try to float through the drop (even when playing in low flows as children will do) or for a person swept into the drop. The provision of signs is advisable.

MAJOR CLASS	SUB CLASS	AESTHETIC PROBLEMS AND SUGGESTIONS	PUBLIC ACCEPTABILITY
SLOPING GROUTED ROCK	SINGLE ROCK LAYER; STACKED BOULDERS Interlocked and stepped	Sloping Grouted Rocks, using a single layer of rock and stacked boulders are aesthetics if the grout is held down and not readily visible, and if care is taken to orient the boulders to fit together, and terrace with horizontal planes on the top. Random pieces which stick up in points and completly different shapes than other rocks look bad, while random rocks which are higher and of a similiar profile are attractive. Adjacent planting and non-linear edges can add to the appearance. Matching grout color so it blends and doesn't contrast is an economical measure, but one which also requires field testing for the rock being utilized.	The public acceptability of these and the Stacked Boulders is the best. The environmental community will likely be pleased.

MAJOR CLASS	SUB CLASS	AESTHETIC PROBLEMS AND SUGGESTIONS	PUBLIC ACCEPTABILITY
SLOPING RIPRAP	GRADED ROCK	Sloping Graded Riprap Drops are aesthetically more appealing than many of the other drops. However, this varies considerably with care taken during construction. If the drop is having a lot of rock movement, or large rock pieces are protruding to form odd and completely "unnatural" profiles, then the appearance is poor. If the rock is well graded and placed, and holding together the drop begins to resemble a rapid which is appealing. Non-linear edges can add to the appearance. Adjacent Landscaping, treatment of the trickle channel, and the absence of debris and sediment have a lot to do with a good appearance.	The acceptability to the layman depends largely on the care taken during construction and the obvious stability of the drop. The environmental community will generally prefer rock drops over concrete, particularly if it lends itself to wetlands. They may work with fish passage, even without fish ladders, because there are hollows and hydraulic conditions conducive to resting and allowing the fish to set up for high "burst" speeds. The biggest safety hazard is tripping or slipping while walking on the loose rock.
	DERRICK STONE per Corps (large boulders over graded riprap) STACKED BOULDERS (Interlocked and stepped)	Derrick stone and stacked boulder drops probably have a greater potential for excellent aesthetics than all other drops except for grouted boulders (and that is a toss-up depending on whether you like a more finished appearance and if the grout was well done). This is because the rocks can be placed to achieve more of a cascade approach, that can be related to a mountain stream or river, and because the rock still has some randomness that is recognizable and fits together, rather than being a jumble of dumped rocks. Adjacent planting and non-linear edges can add to the appearance. Safety is nearly the best, with the key concern being the open voids.	The public acceptability of these and the grouted boulders is the best.

MAJOR CLASS	SUB CLASS	AESTHETIC PROBLEMS AND SUGGESTIONS	PUBLIC ACCEPTABILITY
VERTICAL HARD BASIN	CONCRETE BASIN	Vertical hard basins using concrete basins can potentially be very bleak and extensive. However, this technique has an aesthetic and cost advantage over, say the SCS Vertical Basin because the side slopes in the basin can be landscaped to near the base width of the channel. Similiar to other structures, appropriate detailing can help the structures to be attractive. Relatively simple architectural treatments can be quite effective such as "buff" color additives, sandblasting and exposed aggregate. Also, form liners can be used. In most applications, plain finishes are acceptable. An opportunity exists to make a nice water feature by projecting the trickle channel invert and providing a drip edge to prevent the nappe from following the wall. The stilling basin can become a nice pool, but it can be a debris and sediment laden. One advantage of this basin is that it can be designed to completely drain, which then tends to provide better self cleaning characteristics. Also, there are opportunities to design public plazas, as long as signs indicate the flood hazard to the public. Landscaping makes a big difference.	Generally, acceptability is good, but this also depends on the overall setting, landscaping, and architectural detailing. These structures would be a barrier to fish passage, and are not well liked by the environmental community. In an urban setting these structures will be acceptable, with the exception that safety is of concern because children (and some adults) will walk the crest wall. The provision of signs and fences at the ends of the wall which force people to go upstream or downstream to cross the channel is worth considering.
	GROUTED ROCK BASIN	Vertical hard basins that utilize grouted rock basins further soften the design appearance. However, this depends on a good deal of care taken during construction. If a plaza were to be incorporated, the rock would have to be carefully selected to provide large flat horizontal surfaces (slabby rock) except for feature rock. Other aspects are the same as the vertical hard basins, with the exception that the basin will be rougher and retains more debris.	Generally, acceptability is good, but this also depends on the overall setting, landscaping, and architectural detailing. These structures would be a barrier to fish passage, and are not well liked by the environmental community (but better than the all concrete basins). In an urban setting these structures are acceptable, with the exception that safety is of concern because children (and some adults) will walk the crest wall. The provision of signs and fences at the ends of the wall which force people to go upstream or downstream to cross the channel is worth considering.
	SCS with Baffle Blocks in Basin	Vertical Hard Basins utilizing the SCS Design (where there is a deeper stilling basin, baffle blocks at the end of the basin, and high vertical walls on the sides) are aesthetically very difficult to deal with because of the large walls and the creation of a large hole enclosed by a box. Architectural treatments aren't as helpful because the walls are enclosed. Fences and handrails on the side walls add to the problem. Also, the view from downstream is quite harsh as the walls project far above downstream channel grades and there is little opportunity to landscape and use plantings effectively. Further, the basin is deeper than others (except for SCS and USBR sloping concrete basins), and is thus difficult to drain, usually requiring a pipe system. It is very likely to catch sediment and debris and become a nuisance, especially because of the small, closely spaced baffles (depending on the design).	Few local installations exist. It is presumed that they wouldn't be nearly as well received as many of the other drops. These structures would be a barrier to fish passage, and wouldn't be reviewed favorably by the environmental community. Safety is of concern because of the crest wall and the basin. The provision of signs and fences at the ends of the wall which force people to go upstream or downstream to cross the channel is worth considering. If a person where swept into the basin, there would be no easy escape route.

MAJOR CLASS	SUB CLASS	AESTHETIC PROBLEMS AND SUGGESTIONS	PUBLIC ACCEPTABILITY
BAFFLE CHUTE		The baffle chutes are more interesting than sloping concrete or vertical drops with large concrete basins, but still can be bleak and harsh to the human eye and not fit very well in a soft or "natural" setting. However, intensive planting, architectural treatments of the baffles and sloping basin using exposed aggregate and "buff" color additives, and form liners which add texture or break up the uniformity of the wall make a significant difference. In fact, there are examples in parks and greenways where the baffle drop, so treated, is an asset.	Generally, acceptability is good. However, this also depends on the overall setting, landscaping, and architectural detailing. These structures would be a barrier to fish passage, and are not well liked by the environmental community. In an urban setting these structures will be more acceptable for a perennial stream. Safety, in terms of being swept into the baffles, is a concern, but no cases of people being hurt have been reported to the District. Safety fences, rails or other screening is needed at the walls.
VERTICAL RIPRAP BASIN		With appropriate detailing vertical riprap basins can be attractive. Relatively simple Architectural treatments can be quite effective such as "buff" color additives, sandblasting and exposed aggregate. Also, form liners can be used. But even with good form work the walls are acceptable. An opportunity exist to make a nice water feature by projecting the trickle channel invert and providing a drip edge to prevent the nappe from following the wall. The loose riprap stilling basin can become a nice pool, but often becomes a debris and sediment basin. Taking care to consider maintenance access helps, and encouraging some screeing (or concealing in terms of the debris) can help. Landscaping makes a big differance.	Generally, acceptability is good, but this also depends on the overall setting, landscaping, and architectural detailing. These structures would be a barrier to fish passage, and are not well liked by the Environmental Community. In an urban setting, these structures will be acceptable, with the exception that safety is of concern because children (and some adults) will walk the crest wall. The provision of signs and fences at the ends of the wall which force people to go upstream or downstream to cross the channel is worth considering.

MAJOR CLASS	SUB CLASS	CONSTRUCTION CONCERNS: COMMENTS ON DIFFICULTY TO CONSTRUCT	MATERIALS AVAILIABILITY AND QUALITY CONCERNS: TYPE	MATERIALS AVAILIABILITY AND QUALITY CONCERNS: CONCERN	QUALITY CONTROL MEASURES AND INSPECTION
OTHERS					
SLOPING CONCRETE	SAF Saint Anthony Falls Basin (Sloping Basin with Baffle Blocks in Basin) and Similiar BurRec Basins	The comments presented for Baffle Chute are appropriate, with additional concerns on measures to provide drainage for the stilling basin and adequate transition riprap.	See Baffle Chutes		See Baffle Chutes
	Conventional				
SOIL CEMENT, ROLLERCRETE		As the structures are a type of mass dam, seepage, foundation conditions, and stability of the stilling basin are important concerns. Each of these requires specific techniques of analysis and inspection. The materials of construction, and placement techniques vary. The quality control with soil cement is critical as to cement content, moisture and the silt and clay content (which lead to lower strength). Extensive quality control tests are necessary. Rollercrete is basically a technique which places low moisture content concrete using earthwork equipment. There are instances where this has been used for detention ponds.			Initial items which are especially important are site water control and foundation conditions. The Engineer who established the design assumptions and calculated the required cutoffs should inspect the cutoff for each drop, and adjust the cutoff for the conditions encountered. During construction there are numerous items which provide the correct seepage control and other cutoff techniques that may be called for, preparation of the subgrade for the basin, installation of the proper drains and weeps in the basin, and extensive materials testing.

MAJOR CLASS	SUB CLASS	CONSTRUCTION CONCERNS: COMMENTS ON DIFFICULTY TO CONSTRUCT	MATERIALS AVAILABILITY AND QUALITY CONCERNS: TYPE	MATERIALS AVAILABILITY AND QUALITY CONCERNS: CONCERN	QUALITY CONTROL MEASURES AND INSPECTION
SLOPING GROUTED ROCK	SINGLE ROCK LAYER	The Sloping Grouted Rock Drops have good potential, but requires significant control efforts. Grouting of the voids eliminates the lift potential because circulation under the rock is prevented. In fact, the hydrodynamic forces are relatively minor, but seepage uplift forces are significant. Seepage analysis is required to determine a compatible combination of cutoff depth, location of the toe drain or other drains, and the thickness of rock and grout. Rock problems with specific gravity, durability and hardness are of concern. Gradation problems are largely eliminated because all of the rock has to meet minimum physical dimensions and/or weights, which is much easier to observe and enforce. The greatest danger lies with a "sugar coated" grout job, where the grout doesn't penetrate the voids between the rock and the subgrade, leaving a direct piping route under the grout. This can easily occur when attempting to grout graded riprap, thus the need to use rock that is thicker than the grout layer so that the contractor and the inspector can see and have grout placed directly to the subgrade. The best balance appears to have rock 33 to 50% greater in size than the grout thickness, but of an overall mass sufficient to offset uplift. Also, when holding grout to this level, the appearance will be much better. The handling of the large boulders requires skilled manpower and specialized equipment as discussed above for Stacked Boulders. Equipment similiar to logging tongs, and specially modified buckets with hydraulically powered "thumbs" have been provided in recent years which greatly improve quality and placement rates. The careful placement of stacked boulders, so that the upstream rock is keyed in behind the downstream, and placed with a large flat surface horizontal has been demonstrated to be sucessful.	Riprap	Hardness is of concern because the rock is subject to rough handling and impact forces. Durability concerns are: oxidation, weathering (freeze thaw tests), and leaching or dissolving by water. Fracturing, which leads to odd or undesirable shapes, is to be avoided. Seams or other discontinuities that lead to breakup or undesirable shapes and damage during handling. Geologic type is important; sedimentary rocks are undesirable. Often, volcanic rock has low density problems. Density of the rock requires specific density tests. Availiability can be a problem because quarries presently stockpile larger boulders as they occur in normal operations, thus quarries warn that production can be slow. This firm hasn't experienced problems with this, but have had problems with undersized material when specifications weren't clear on minimum dimensions in all axes.	Preconstruction items include an intensive review of the basic technique for cutoff construction, seepage control under the grouted rock, placement of the rock, placement of the grout including pumping, grout flow control (off, on, and rate) and vibration, and additives including fibers for shrinkage crack control, toughness and color additives. A significant effort is needed in the area of rock quality control (see discussion on sloping graded riprap and stacked boulders). The problems with fracturing and seams, leading to rock splitting, needs to be carefully reviewed and a hard line with the quarry taken. Initial items which are especially important are site water control, foundation conditions, cutoffs, toe drains and other drains and cutoffs that may be required for a particular design. The designer should inspect the subgrade and cutoff trench to see how it compares to design assumptions, and appropriate adjustment should be made. As with other large boulder drops, it is preferable to locate the cutoff upstream to allow the construction areas to be separated. Specifications should include requirements for orderly procedures and appropriate equipment. Difficulty in placement shouldn't be allowed as an excuse. The toe drain and other drains should be placed and protected from contamination, particulary when the grout is placed latter. Specifications should include requirements for appropriate equipment, both for rock and grout placement. Difficulty in placement shouldn't be allowed as an excuse. The work is similiar to graded riprap, but major care has to be taken to arrange matching faces, to key in upstream rocks below the tops of downstream rocks, and orient exposed faces as desired (top surface horizontal seems to be preferable for both aesthetic and hydraulic reasons). It is important to get good placement for the trickle channel and so there is no secondary drop. It is a good idea to meander the trickle channel in the basin and allow even larger boulders to obstruct the flow to dissipate the stronger jet there (much like the baffle block drop. The key to success is: to use rock that is no smaller in any dimension than the desired grout thickness (so that one can fully penetrate the voids), to pump and place the grout with a nozzle that can go to the subgrade, to have good control of the grout mix (too wet creates shrinkage cracks and stability problems on slope, too dry leads to poor penetration), to place the grout to the desired thickness (a minimum is needed for uplift, and placing too much is unattractive and smooths out the roughness of the drop which is needed to prevent the jump from washing downstream), and to vibrate using a "pencil vibrator" to penetrate the voids between and under rock. During grouting, it is important to protect the toe drains. With care it is not necessary to get grout on the top of the rock, but any spillage should be washed off (a small amount of water won't hurt the grout between rock). If a massive amount of cleaning is necessary, the grout is too high. A wood float leaves a nice finish, but the vibrator will generally leave a satisfactory appearance with some touch-up. Full time inspection is required during grouting, as is periodic inspection during the rock placement depending upon the performance of the contractor and the aesthetic appearance desired.
	STACKED BOULDERS Interlocked and stepped	The bottom line for Sloping Grouted Rock and Grouted Stacked Boulders is that there are quite a few sucessful examples which illustrate great potential. In fact, the UDFCD has often repaired riprap structures using grout. On the other hand, there are examples of sugar coated graded riprap and smaller rock drops which have failed. In extremely erosive silts and fine sand, there are examples of failures due to poor cutoff and poor grouting (not penetrating the void under the rock). Grouted Rock is also in the developing phase locally, and involves some risk taking (but less than ungrouted) that appears worthwhile.	Grout	Cement Content and type is important for strength and durability. Aggregate represents an important tradeoff between strength/durability and workability. Water content effects another tradeoff between workability and strength and also greatly influences shrinkage cracking. There are synthetic fibers which can be mixed in, which aids crack control and durability.	
			Other Items	See descriptions for concrete, reinforcing, and materials for drains. Sheetpile comes in many configurations and, in particular, joint details. It requires both geotechnical, structural, hydraulic and driving expertise. See discussion under Derrick Stone and Stacked Boulders.	

MAJOR CLASS	SUB CLASS	CONSTRUCTION CONCERNS: COMMENTS ON DIFFICULTY TO CONSTRUCT	MATERIALS AVAILIABILITY AND QUALITY CONCERNS: TYPE	MATERIALS AVAILIABILITY AND QUALITY CONCERNS: CONCERN	QUALITY CONTROL MEASURES AND INSPECTION
	STACKED BOULDERS (Interlocked and stepped) (CONTINUED)	rates through the voids. The sheetpile used by the Corps manages this problem for Derrick Stone. Stacked Boulders below Culverts are successful because the culvert provides seepage control. Grouted rock and slurry cutoffs have been successful. The careful placement of stacked boulders, such that the upstream rock is keyed in behind the downstream, and placed with a large flat surface horizontal has been demonstrated to be sucessful. There is a greater degree of stability with angular/cubical quarry rock than rounded river boulders.		Availiability can be a problem because quarries presently stockpile larger boulders as they occur in normal operations, thus quarries warn that production can be slow. This firm hasn't experienced problems with this, but have had problems with undersized material when specifications weren't clear on minimum dimensions in all axes.	disturb and seepage cutoffs. Landscape treatments make a BIG DIFFERENCE, so take care and work with experienced professionals.
		Stacked boulders are attractive with a little care and guidance during installation. Basically, both are options still in the developing phase locally, and involve some risk taking that appears worthwhile.	Other Items	See descriptions for concrete, reinforcing, and grout as used in cutoffs. Sheetpile comes in many configurations and in particular joint details. It requires geotechnical, structural, hydraulic and driving expertise to evaluate compatible soils conditions, driving conditions and driving equipment, and the correct pile section, materials characteristics (eg. Cor-Ten for corrosion resistance), and strength characteristics.	

MAJOR CLASS	SUB CLASS	CONSTRUCTION CONCERNS — COMMENTS ON DIFFICULTY TO CONSTRUCT	MATERIALS AVAILIABILITY AND QUALITY CONCERNS — TYPE	MATERIALS AVAILIABILITY AND QUALITY CONCERNS — CONCERN	QUALITY CONTROL MEASURES AND INSPECTION
SLOPING RIPRAP	GRADED ROCK	Sloping Riprap Drops are the easiest drops to construct incorrectly and, at best, are the drops that will still fail even when all parties involved are trying their best. They are beset with quality problems in terms of rock that deteriorates; rock that is undersized; rock that doesn't meet specific gravity specifications; and gradation requirements that are not met. Rock installation is difficult in regard to measuring performance and maintaining consistancy. Either at the quarry or in the field, a change in manpower can result in changes in quality. There are great variations in what is acceptable to one inspector from the next (and the design engineers), and definitions such as well graded, voids chinked, and placement grades are widely interpreted. Unfortunately, this combines with a technical situation where a very complex phenomena leaves many unknowns, and, thus, guesswork and judgements based on experience are made. (This is not a criticism of anyone, but a simple recognition that a completely satisfactory technology does not exist, thus the need to go on experience). A misunderstanding occurs because of the term dumped riprap, that one can back up the truck, dump it and grade it out. This is NOT what is required. At the quarry, segregation is an automatic occurrence. The operator attempts to mix by eyeball selection from different parts of or piles of sizes. Hauling and dumping again results in segregation with larger material on the bottom. Thus, in the field, great care is required to redistribute the rock to a graded mix, where there is a good distribution of larger pieces on the surface to anchor and support the other sizes. --See Section X and XII for further discussion.	Riprap	Hardness is of concern because the rock is subject to rough handling and impact forces. Durability concerns are: oxidation, weathering (freeze thaw tests), and leaching or dissolving by water. Fracturing which leads to odd or undesirable shapes. Seams or other discontinuities that lead to breakup or undesirable shapes and damage during handling. Geologic type is important; sedimentary rocks are undesirable. Often, volcanic rock has low density problems. Density of the rock requires specific density tests. Gradation of riprap is critical, with major descrepancies common in the larger sizes. Eyeballing a gradation is unreliable, and a major source of error. Availiability can be a problem because quarries cannot keep large stockpiles of every gradation.	Preconstruction items include a brief check of any reinforcing steel and concrete mix. The basic technique for cutoff construction should be reviewed to assure that cutoff will be achieved. The most critical effort has to be in the area of rock quality control. This should include laboratory tests of hardness, durability and density. Particularly on projects greater than 5000 tons, tests should be performed for the particular project, rather than relying on previous tests. Many quarries have problems with fracturing and seams, that leads to rock splitting into smaller pieces by the time the rock is placed at the site. This requires quarry and field monitoring, and disapproving a quarry for particular types of projects (those using larger stone). Initial items which are especially important are site water control and foundation conditions. The Engineer who established the design assumptions and calculated the required cutoffs should inspect the cutoff for each drop, and adjust the cutoff for the conditions encountered. During construction, the crest cutoff wall needs to be properly graded for good crest control, and constructed and backfilled for seepage control. It is critical to test the gradation of the subsoil, and confirm the gradation of the bedding to be installed. The bedding must be properly placed. Then a major effort is required to sustain quality control at the quarry and at the site. The key items would include actual gradation tests, preservation of a test pile, and placed test samples, use of photographic comparisons using a large plastic overlay grid of the approved rock both in a stockpile and placed condition. GREAT care has to be taken to assure that the largest pieces end up on the surface with the tops flush to finish grade. They should act as anchors, with other larger pieces evenly interspersed with voids filled with a well graded mixture of the remaining pieces between. The concept is to have a tight formation with a minimization of voids, creating a solidly packed mass. A key concept is to have material on the surface that isn't smaller than the d50, because the theories of movement and practice have demonstrated that smaller material will be quickly moved. This is a friendly battle at best! It is important to get good placement for the trickle channel and so there is no secondary drop. Finish work includes minor transition rock placement with care not to disturb seepage cutoffs. Landscape treatments make a BIG DIFFERENCE, so take care and work with experienced professionals.
			Other Items	See descriptions for concrete, reinforcing, and grout as used in cutoffs.	
	DERRICK STONE per Corps (large boulders over graded riprap) STACKED BOULDERS (Interlocked and stepped)	The derrick stone and stacked boulder approaches have more promise for successful construction than graded riprap, but, have the same problems with specific gravity, durability and hardness. The gradation problems are largely eliminated because all of the critical surface layers have to meet minimum physical dimensions and/or weights, which are much easier to observe and enforce. The problems with bedding layers are worse, because a layer of graded riprap needs to be provided as a intermediate bedding layer over the gravel size bedding layer. The handling of the large boulders requires skilled manpower and specialized equipment. Handling with an ordinary backhoe is generally inadequate because it can't orient the boulders for the best match of abutting surfaces (to minimze voids), and to achieve desired surface orientation. Equipment similiar to logging tongs, and specially modified buckets with hydraulically powered "thumbs" have been provided in recent years which greatly improve quality and placement rates. The biggest problem for Stacked Boulders and Derrick Stone is for potential headcutting caused by large potential flow	Riprap	Hardness is of concern because the rock is subject to rough handling and impact forces. Durability concerns are: oxidation, weathering (freeze thaw tests), and leaching or dissolving by water. Fracturing which leads to odd or undesirable shapes is to be avoided. Seams or other discontinuities that lead to breakup or undesirable shapes and damage during handling. Geologic type is important; sedimentary rocks are undesirable. Often, volcanic rock has low density problems. Density of the rock requires specific density tests.	Preconstruction items include an intensive review of the basic technique for cutoff construction. As with graded riprap, the most critical effort has to be in the area of rock quality control (see discussion on sloping graded riprap). The problem with fracturing and seams, leading to rock splitting needs to be carefully reviewed and a hard line with the quarry taken. Initial items which are especially important are site water control, foundation conditions, and the potential for headcutting. This requires more effort than sloping graded riprap. The best hint is to move the cutoff upstream to allow the construction areas to be separated, or use a large zone of well graded and densely packed graded riprap depending on site conditions. Specifications should include requirements for orderly procedures and appropriate equipment. Difficulty in placement shouldn't be allowed as an excuse. The work is similiar to graded riprap, but major care has to be taken to arrange matching faces, to key in upstream rocks below downstream rocks (for stacked boulders, tops are flush along the slope for Derrick Stone), and orient exposed faces as desired (top surface horizontal for Stacked). It is important to get good placement for the trickle channel and so there is no secondary drop. Finish work includes minor transition rock placement including care not to

MAJOR CLASS	SUB CLASS	CONSTRUCTION CONCERNS: COMMENTS ON DIFFICULTY TO CONSTRUCT	MATERIALS AVAILABILITY AND QUALITY CONCERNS: TYPE	MATERIALS AVAILABILITY AND QUALITY CONCERNS: CONCERN	QUALITY CONTROL MEASURES AND INSPECTION
VERTICAL HARD BASIN	CONCRETE BASIN	The foundation and seepage concerns are very critical with regard to the vertical wall. It is not as critical as for the vertical riprap drop, but poor construction and seepage control can result in sudden failure. The use of caissons or pile can mitigate this effect. Put in comparative terms with the baffle chute, seepage problems will result in displacement of the vertical wall with no warning, where the box like structure of the baffle chute may evidence some movement or cracking but not total failure and allow time for repairs. The quality control concerns and measures for reinforced concrete are described under baffle chutes. The foundation concerns for the wall are critical as described above. The subsoil conditions for the basin are also important so that the basin concrete or grouted riprap is stable against uplift pressures. See Sloping Grouted Rock for concerns. The key concern is seepage relief and adequate thickness. The roughness of the basin is useful in shortening the basin, but it is difficult to control the contractor from overplacement, particularly if he is on a unit price basis.	Concrete	The major concern is strength and ability to resist weathering. Aggregate strength and durability is important, along with color and shape for exposed aggregate for architectural treatments, and concrete color additives.	Preconstruction items include all of the items under baffle chutes for concrete work, with effort emphasized for seepage control and measures related to the stability of the basin, whether it be reinforced concrete or grouted rock. Initial items which are especially important are site water control and foundation conditions. The engineer who established the design assumptions and calculated the required cutoffs should inspect the cutoff for each drop, and adjust the cutoff for the conditions encountered. Any architectural test samples should be completed and approved, along with all coatings, weather protection or other items which could affect appearance. During construction there are numerous items which require checking including those described for both baffle chutes and sloping grouted rock plus the following: careful backfill of the wall to provide the correct seepage control and other cutoff techniques that may be called for, preparation of the subgrade for the basin, installation of the proper drains and weeps in the basin, steel and concrete placement including construction and expansion joints in the concrete basin, and proper rock and grout placement for grouted rock basins. Finish work includes minor transition rock placement taking care not to disturb seepage cutoffs, linings or drains. It is important to get good placement so that flow is directed into the trickle channel and so there is no secondary drop. Landscape and architectural treatments make a BIG DIFFERENCE, so take care and work with experienced professionals.
			Rein-forcing Steel	Usually not a problem unless the wrong grade of steel brought to job, or site conditions are conducive to corrosion.	
			Riprap	See discussion under sloping riprap drops, but quality in terms of material integrity, size, and gradation is alway of concern.	
	GROUTED ROCK BASIN	The bottom line is that this type of structure has a moderate level of difficulty. The wall, once foundation conditions are addressed, is easy. It is very possible for the construction of the seepage control and earthwork to go awry and problems undetected until the time of failure. The flat concrete or grouted rock placement is easier for the contractor than sloping or other rock drops, but again poor placement and undetected subsoil, bedding or rock problems can result in failure. Thus, it is easier than many others to build but susceptible to some hidden risks and problems, and sudden failures (but less than vertical riprap drops).	Grouted Rock	The quality of grout is critical. If the slump is too high, grout strength will be weak and shrinkage cracks will multiply. If too low, placement is more difficult and voids underneath can increase, setting up a piping failure. Adequate rock size and elimination of all rock smaller than the grout thickness can be of concern for delivery schedule, expense, and handling (although this more often turns out not to be true).	
			Arch-itectural Items	Coatings are always subject to quality concerns, which are compounded by substrate conditions.	
			Landscape Items	Plantings are subject to a wide variety of quality and size.	
	SCS with Baffle Blocks in Basin				

MAJOR CLASS	SUB CLASS	CONSTRUCTION CONCERNS: COMMENTS ON DIFFICULTY TO CONSTRUCT	MATERIALS AVAILIABILITY AND QUALITY CONCERNS: TYPE	MATERIALS AVAILIABILITY AND QUALITY CONCERNS: CONCERN	QUALITY CONTROL MEASURES AND INSPECTION
BAFFLE CHUTE		There are numerous steps necessary, but they are easily controlled by a contractor. For quality control and inspection there are consistent, measurable, and repeatable standards to apply, except for foundation problems; and the usual problems with riprap, that it isn't usually as critical to the entire structure. There are problems in detailing the finish work with regard to architectual and landscape treatments. Formwork, form ties, and seal coatings can leave a poor appearance, and surface finishes are often botched by personnel (both by the contractor and inspectors) not familiar with the appropriate techniques. In summary, this type of structure is the more successful as far as performance and is straightforward to construct.	Concrete	The major concern is strength and ability to resist weathering. Aggregate strength and durability is important, along with color and shape for exposed aggregate for architectural treatments, and concrete color additives. In the coming years, with the new airport construction, availability could become a concern, but this is not a problem now.	Preconstruction items include shop drawings for reinforcing steel, formwork patterns and ties, concrete design mix and related tests, color additives or coatings (always call for the red tinted sealant, not the white as the red dries clear and is not nearly as harsh), and architectural treatments such as form liners, handrails and fences. Initial items which are especially important are site water control and foundation conditions. The Engineer who established the design assumptions and calculated the required cutoffs should inspect the cutoff for each drop, and adjust the cutoff for the conditions encountered. Any architectural test samples should be completed and approved, along with all coatings, weather protection or other items which could affect appearance. During construction there are numerous items which require checking including: water control, rebar placement, formwork, tie placement, weep holes and drains, form release coatings and form cleaning before concrete placement, concrete placement and testing, weather protection, form removal, sealants, tie hole treatment, concrete finish work, and earthwork (especially that related to seepage control. There are many items, but they are easily and quickly checked. Finish work includes rock placement. Take care not to disturb seepage cutoffs, linings or drains. Riprap quality control is best described under the riprap drops, but it is important to get good placement so that flow is directed into the trickle channel and so there is no secondary drop. Alternative stilling basins of reinforced concrete or grouted rock need to address the same concerns. Landscape and architectural treatments make a BIG DIFFERENCE, so take care and work with experienced professionals.
			Reinforcing Steel	Usually not a problem unless the wrong grade of steel brought to job, or site conditions are conducive to corrosion problems.	
			Riprap	See discussion under sloping riprap riprap drops, but quality in terms of material integrity, size, and gradation is alway of concern.	
			Architectural Items	Coatings are always subject to quality concerns, which are compounded by substrate conditions.	
			Landscape Items	Plantings are subject to a wide variety of quality and size.	
VERTICAL RIPRAP BASIN		The foundation and seepage concerns are very critical with regard to the vertical wall. It is also generally more critical than an equivalent drop for a vertical drop into a hard basin because the riprap basin may scour and reshape, leaving less supporting material on the downstream side. Thus, if seepage is worse than anticipated, backfill is poor, or if seepage control measures aren't functioning, an immediate and severe structure stability problem can occur. The use of caissons or pile can mitigate this effect. Put in comparitive terms with the baffle chute, seepage problems will result in displacement of the vertical wall with no warning, where the box like structure of the baffle chute may evidence some movement or cracking but not total failure which will allow time for repairs. There are numerous concerns with riprap. They are described under sloping riprap. The problem here with undersized material is again that the basin will reshape differently and result in stability problems for both the wall and the basin. The bottom line is that this type of structure has a moderate level of difficulty. The wall, once foundation conditions are addressed, is easy. It is very possible for the construction of the seepage control and earthwork to go awry and for problems to go undetected until the time of failure. The flat riprap placement is easier than sloping or other rock drops, but again poor placement and undetected subsoil, bedding or rock problems can result in failure. Thus, it is easier than many others to build but susceptible to hidden risks and problems, and sudden	Concrete	The major concern is strength and ability to resist weathering. Aggregate strength and durability is important, along with color and shape for exposed aggregate for architectural treatments, and concrete color additives. In the coming years, with the new airport construction availability could become a concern, but this is not a problem now.	Preconstruction items include all of the items under baffle chutes for concrete work plus all the items related to riprap as described under sloping riprap drops, especially as to size of material and compatible bedding material for the riprap and the actual soils encountered. Initial items which are especially important are site water control and foundation conditions. The Engineer who established the design assumptions and calculated the required cutoffs should inspect the cutoff for each drop, and adjust the cutoff for the conditions encountered. Any architectural test samples should be completed and approved, along with all coatings, weather protection or other items which could affect appearance. During construction, there are numerous items which require checking including those described for both baffle chutes and sloping riprap plus the following: careful backfill of the structure to provide the correct seepage control and other cutoff techniques that may be called for. The riprap and bedding placement should comply with the sizes and types called for, thus gradation tests of both are essential. Eyeballing doesn't work. Finish work includes rock placement including care not to disturb seepage cutoffs, linings or drains. Riprap quality control is described under sloping riprap drops, but it is important to get good placement so that flow is directed into the trickle channel and so there is no secondary drop. Landscape and architectural treatments make a BIG DIFFERENCE, so take care and work with experienced professionals.
			Reinforcing Steel	Usually not a problem unless the wrong grade of steel brought to job, or site conditions are conducive to corrosion problems.	
			Riprap	See discussion under sloping riprap drops, but quality in terms of material integrity, size, and gradation is alway of concern.	
			Architectural Items	Coatings are always subject to quality concerns, which is compounded by substrate conditions.	
			Landscape Items	Plantings are subject to a wide variety of quality and size.	

MAJOR CLASS	SUB CLASS	FLOW AND DROP HEIGHT SUITABILITY MATRIX

OTHERS

MAJOR CLASS	SUB CLASS	HEIGHT	0 TO 500 CFS	500 TO 7500 CFS	7500 TO 15000 CFS
SLOPING CONCRETE	SAF Saint Anthony Falls Basin (Sloping Basin with Baffle Blocks in Basin) and Similiar BurRec Basins	2 FT.	Hydraulically OK but cost economy doubtful except for difficult situations.	Hydraulically OK but cost economy doubtful except for difficult situations.	Hydraulically OK but cost economy doubtful except for difficult situations. Contraction may help.
		4 FT.	Application doubtful because of basin depth, poor adaptability to degraded bed, safety, and economy.	Application doubtful because of basin depth, poor adaptability to degraded bed, safety, and economy.	Application doubtful because of basin depth, poor adaptability to degraded bed, safety, and economy.
		6 FT.	Application doubtful because of basin depth, poor adaptability to degraded bed, safety, and economy.	Application doubtful because of basin depth, poor adaptability to degraded bed, safety, and economy.	Application doubtful because of basin depth, poor adaptability to degraded bed, safety, and economy.
		8 FT.	Application doubtful because of basin depth, poor adaptability to degraded bed, safety, and economy.	Application doubtful because of basin depth, poor adaptability to degraded bed, safety, and economy.	Application doubtful because of basin depth, poor adaptability to degraded bed, safety, and economy.
	Conventional	12 FT.	Application doubtful because of basin depth, poor adaptability to degraded bed, safety, and economy.	Application doubtful because of basin depth, poor adaptability to degraded bed, safety, and economy.	Application doubtful because of basin depth, poor adaptability to degraded bed, safety, and economy.

MAJOR CLASS	HEIGHT	0 TO 500 CFS	500 TO 7500 CFS	7500 TO 15000 CFS
SOIL CEMENT, ROLLERCRETE	2 FT.	Special Situation depending on site, situation and materials.	Special Situation depending on site, situation and materials.	Special Situation depending on site, situation and materials.
	4 FT.	Special Situation depending on site, situation and materials.	Special Situation depending on site, situation and materials.	Special Situation depending on site, situation and materials.
	6 FT.	Special Situation depending on site, situation and materials.	Special Situation depending on site, situation and materials.	Special Situation depending on site, situation and materials.
	8 FT.	Special Situation depending on site, situation and materials.	Special Situation depending on site, situation and materials.	Special Situation depending on site, situation and materials.
	12 FT.	Special Situation depending on site, situation and materials.	Special Situation depending on site, situation and materials.	Special Situation depending on site, situation and materials.

MAJOR CLASS	SUB CLASS	HEIGHT	0 TO 500 CFS	500 TO 7500 CFS	7500 TO 15000 CFS
		FLOW AND DROP HEIGHT SUITABILITY MATRIX			
SLOPING GROUTED ROCK	SINGLE ROCK LAYER	2 FT.	Yes. Takes extra effort in construction. Seepage control is important.	Yes. Takes extra effort in construction. Seepage control is important.	Yes. Takes extra effort in construction. Seepage control is important.
		4 FT.	Yes. Takes extra effort in construction. Seepage control is important.	Yes. Takes extra effort in construction. Seepage control is important.	Yes. Takes extra effort in construction. Seepage control is important.
		6 FT.	Yes. Takes extra effort in construction. Seepage control is important.	Cutoff and Seepage is critical. Effort requires soils testing, seepage and quality control.	Cutoff and Seepage is critical. Effort requires soils testing, seepage and quality control.
		8 FT.	Yes. Takes extra effort in construction. Seepage control is important.	Cutoff and Seepage is critical. Effort requires soils testing, seepage and quality control.	Cutoff and Seepage is critical. Effort requires soils testing, seepage and quality control.
		12 FT.	Yes. Takes extra effort in construction. Seepage control is important.	Cutoff and Seepage is critical. Effort requires soils testing, seepage and quality control.	Cutoff and Seepage is critical. Effort requires soils testing, seepage and quality control.
	STACKED BOULDERS Interlocked and stepped				

FLOW AND DROP HEIGHT SUITABILITY MATRIX

MAJOR CLASS	SUB CLASS	HEIGHT	0 TO 500 CFS	500 TO 7500 CFS	7500 TO 15000 CFS
SLOPING RIPRAP	GRADED ROCK	2 FT.	Yes. Takes extra effort in construction.	Yes. Takes extra effort in construction.	Yes. Takes extra effort in construction.
		4 FT.	Yes. Use flatter slopes, 6 - 10 hor. to 1 vert. advisable. Takes extra effort in Construction.	Yes. Use flatter slopes, 6 - 10 hor. to 1 vert. advisable. Takes extra effort in Construction.	Yes. Use flatter slopes, 6 - 10 hor. to 1 vert. advisable. Takes extra effort in Construction.
		6 FT.	Possibly, for rundowns and local drainage. Take care on rock sizing and slope, and construction.	No.	No.
		8 FT.	Possibly, for rundowns and local drainage. Take care on rock sizing and slope, and construction.	No.	No.
		12 FT.	Possibly, for rundowns and local drainage. Take care on rock sizing and slope, and construction.	No.	No.

MAJOR CLASS	SUB CLASS	HEIGHT	0 TO 500 CFS	500 TO 7500 CFS	7500 TO 15000 CFS
SLOPING RIPRAP	DERRICK STONE per Corps (large boulders over graded riprap)	2 FT.	Yes. Takes extra effort in construction. Allows a shorter drop length if seepage handled.	Yes. Takes extra effort in construction. Allows a shorter drop length if seepage handled.	Yes. Takes extra effort in construction. Allows a shorter drop length if seepage handled.
		4 FT.	Yes. Takes extra effort in construction. Allows a shorter drop length if seepage handled.	Yes. Takes extra effort in construction. Allows a shorter drop length if seepage handled.	Yes. Takes extra effort in construction. Allows a shorter drop length if seepage handled.
	STACKED BOULDERS (Interlocked and stepped)	6 FT.	Possibly, for rundowns and local drainage. Take care on rock sizing and slope, and construction.	Generally not, but there are circumstances such as corrective work, and drops with special foundations that may be considered after extensive analysis.	Generally not, but there are circumstances such as corrective work, and drops with special foundations that may be considered after extensive analysis.
		8 FT.	Possibly, for rundowns and local drainage. Take care on rock sizing and slope, and construction.	(see 6 FT.)	(see 6 FT.)
		12 FT.	Possibly, for rundowns and local drainage. Take care on rock sizing and slope, and construction.	No.	No.

FLOW AND DROP HEIGHT SUITABILITY MATRIX

MAJOR CLASS	SUB CLASS	HEIGHT	0 TO 500 CFS	500 TO 7500 CFS	7500 TO 15000 CFS
VERTICAL HARD BASIN	CONCRETE BASIN	2 FT.	Yes.	Yes.	Yes.
		4 FT.	Yes, but consider safety and seepage.	Yes, but consider safety and seepage.	Yes, but consider safety and seepage.
		6 FT.	No, safety considerations prohibit.	No, safety considerations prohibit.	No, safety considerations prohibit.
		8 FT.	No, safety considerations prohibit.	No, safety considerations prohibit.	No, safety considerations prohibit.
		12 FT.	No, safety considerations prohibit.	No, safety considerations prohibit.	No, safety considerations prohibit.
	GROUTED ROCK BASIN				
	SCS with Baffle Blocks in Basin				

FLOW AND DROP HEIGHT SUITABILITY MATRIX

MAJOR CLASS	SUB CLASS	HEIGHT	0 TO 500 CFS	500 TO 7500 CFS	7500 TO 15000 CFS
BAFFLE CHUTE		2 FT.	Hydraulically OK but cost economy doubtful except for difficult situations.	Hydraulically OK but cost economy doubtful except for difficult situations.	Hydraulically OK but cost economy doubtful except for difficult situations. Contraction may help.
		4 FT.	Hydraulically OK but cost economy borderline.	Hydraulically OK but cost economy borderline.	Hydraulically OK but cost economy borderline. Reducing the channel width at the drop may help.
		6 FT.	Yes.	Yes.	Yes.
		8 FT.	Yes.	Yes.	Yes.
		12 FT.	Yes.	Yes.	Yes.

MAJOR CLASS	SUB CLASS	HEIGHT	0 TO 500 CFS	500 TO 7500 CFS	7500 TO 15000 CFS
VERTICAL RIPRAP BASIN		2 FT.	Yes.	Yes.	Yes.
		4 FT.	Yes, but consider safety and seepage.	Yes, but consider safety and seepage.	Yes, but consider safety and seepage.
		6 FT.	No, safety considerations prohibit.	No, safety considerations prohibit.	No, safety considerations prohibit. *
		8 FT.	No, safety considerations prohibit.	No, safety considerations prohibit.	No, safety considerations prohibit. *
		12 FT.	No, safety considerations prohibit.	No, safety considerations prohibit.	No, safety considerations prohibit. *

* These drops are used in a riverine environment with sheetpile, buttress walls and other techniques to economize. Hazard to boating.

MAJOR CLASS	SUB CLASS	BASIC HYDRAULIC PHENOMENA	SUGGESTED HYDRAULIC ANALYSIS	HYDRAULIC ANALYSIS DIFFICULTY	OTHER DESIGN HINTS
OTHERS					
SLOPING CONCRETE	SAF Saint Anthony Falls Basin (Sloping Basin with Baffle Blocks in Basin) and Similiar BurRec Basins	Basic energy dissipation is accomplished by conventional hydraulic jump and turbulent flow over rock. Conventional basin is smooth with no more than a sill that rises back up to the downstream channel bottom. Other basins have blocks which cause turbulence and energy dissipation, in a shorter basin.	CREST CONTROL HYDRAULICS TRANSITION HYDRAULICS UPSTREAM BASIN LAYOUT/HYDRAULICS per available literature and design guides. TRICKLE CHANNEL AT CREST DRAINAGE ANALYSIS OF STILLING BASIN, and related piping needs to be undertaken unless wet basin acceptable. SIMILIAR ANALYSIS FOR HYDRAULIC AND ROCK SIZING ANALYSES IN TRICKLE CHANNEL.	-OK -Reasonable, but unusual situations can occur -Reasonably easy to use, caution is appropriate regarding basin depth. -No guidelines available but reasonable to approximate. -Difficult to design a reliable system unless large conduits used.	Use the trickle channel to help drain the basin. Generally is not a very applicable drop because the hydraulic conditions in a grass channel aren't very compatible
	Conventional				
SOIL CEMENT, ROLLERCRETE		SEE APPROPRIATE CATEGORY FOR PROFILE, but most likely Sloping Concrete.			

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APPENDIX B

Example Riprap Specification

PART 1: GENERAL

1-1 DESCRIPTION: The work of this section consists of placement of bedding, rock riprap, grouted rock, and cover stone (Derrick Stone) as indicated.

1-2 SUBMITTALS AND TESTING: In accordance with Section 01300, submit certificate stating both source of stone and certifying materials for all types of riprap will meet the requirements of this section. Including test results for specific gravity, abrasion, and freeze thaw.

In advance of delivery of riprap to the work site an inspection of the quarry shall be arranged by the Contractor and shall include the Contractor, Engineer, and Quarry Representative. The quarry will identify the rock source and procedures that will be used to stockpile, mix and grade the types of riprap specified. For each type of riprap specified a 10 ton minimum random sample (as selected by the Engineer) will be selected at random by the Engineer. The objective is to obtain a sample as it would be handled for normal delivery to the work site. It will then be placed in an approved area at the quarry and sized and sorted to identify and weigh the individual pieces as directed by the Engineer. The Contractor and Quarry Representative shall supply all labor to sort and weigh the riprap. The approved sample shall then be hauled to the work site and stockpiled for comparison of future riprap deliveries. When approximately one-third of all of the specified type of riprap has been delivered to the work site, a second field gradation may be requested by the Engineer to determine compliance to these specifications. The Engineer may at any time, if he deems necessary, require additional field gradations or other tests.

Rock, (for grouting) boulders and cover stone shall be visually checked at the quarry or at the work site as required for size, elongation, cracks, deterioration and other defects visible on the entire surface area of the stone. Five percent of the stone checked for cracks shall be wetted and reinspected for minute cracks to determine if additional inspections are necessary. Stone with cracks or defects that are detrimental to a long lasting product shall not be shipped to the work site.

PART 2: MATERIALS

2-1 RIPRAP:

A. General. Use quarry stone which is sound and durable against disintegration under conditions to be met in handling and placing, and is hard and tenacious and otherwise of a suitable quality to ensure permanency in the specified kind of work.

The color of the riprap **(shall be __________ and)** must be approved by the Engineer. Once approved, the color shall be kept consistent through the project.

All stone shall be angular, each piece having its greatest dimensions not greater than 3 times its least dimensions and shall conform to the following test requirements of the American Society for Testing Materials Standards:

	Requirement	ASTM Standard
Apparent specific gravity, minimum	2.60	C-127-59
Abrasion, maximum percent	45	C-535-65
Freeze thaw loss, maximum percent after 12 cycles	10	AASHTO 103 Procedure A

Concrete masonry or concrete pavement may not be used for riprap. The gradation requirements for ordinary riprap shall be as follows (approximate weight assumes spherical shape which more closely approximates the weight of the individual stone):

CLASSIFICATION AND GRADATION OF ORDINARY RIPRAP

Riprap Designation	% Smaller Than Given Size By Weight	Intermediate Rock Dimension (Inches)	Approximate[1] Min-Rock Weight (Pounds)	d_{50}* (Inches)
Type VL	70-100	12	85	
	50-70	9	36	
	35-50	6	11	6**
	2-10	2	0.4	
Type L	70-100	15	166	
	50-70	12	85	
	35-50	9	36	9**
	2-10	3	1.3	
Type M	70-100	21	455	
	50-70	18	287	
	35-50	12	85	12
	2-10	4	3	
Type H	100	30	1327	
	50-70	24	680	
	35-50	18	287	18
	2-10	6	11	
Type VH	100	42	3642	
	50-70	33	1767	
	35-50	24	680	24
	2-10	9	36	

1 Based on Specific Gravity = 2.60

*d_{50} = Mean particle size

** Bury types VL and L with 6-inches top soil and revegetate to protect from vandalism.

B. Boulders. The boulders shall range in size from **(30 to 42-)**inches, with an average size of approximately **(36-)**inches. The minimum dimension of the boulders in any direction shall be **(30-)**inches, 20% (minimum) shall be a minimum of **(36-)** inches in each of two dimensions.

C. Cover Stone. The cover stone shall consist of stone meeting the requirements of riprap as specified in this section and shall be in pieces approximately square in cross-section, free from thin slabby pieces having a maximum dimensin more than two times the least dimension. Quarry operations shall be controlled to produce a reasonably uniform stone of the size required by the Drawings. Unless modified by the Contract Drawings, cover stone shall have a minimum cross-sectin dimension of **(38-)**inches and a maximum cross-section dimension of **(48-)**inches with an adverse cross-section dimension of **(44-)**inches. Stones of this size in a shape midway between a sphere and a cube should weigh approximately **(4,000 - 8,000 lbs).** If stone is more rectangular in shape the weight will be considerbly more. Dirt, fines, and smaller stones accumulated from blasting or handling shall not exceed 5 percent by weight.

D. Grouted Rock. Rock for grouting shall consist of stone meeting the requirements of riprap specified in this section with the minimum size of the rock in any dimension greater than the nominal grout thickness or rock size called out on the Drawings. Wash the rock free of fines or soil which would affect the grout bond.

2-2 BEDDING: Use porous, free-draining material, consisting of sand, gravel, crushed stone or other approved free-draining material. On-site materials shall be used if available when approved by the Engineer. Imported materials shall be used if no on-site materials are available. All materials shall meet the following gradation requirements:

GRANULAR BEDDING GRADATION

U.S. Standard Sieve Size	Percent by Weight Passing Square Mesh Sieves	
	Type I	Type II
3-inch	-	100
1-1/2-inch	-	-
3/4-inch	-	20-90
3/8-inch	100	-
No. 4	95-100	0-20
No. 16	45-80	-
No. 50	10-30	-
No. 100	2-10	-
No. 200	0-2	0-3

2-3 GROUT: Concrete for the grout shall be an approved batch meeting the following requirements: All concrete shall develop 4,000 psi compressive strength within 28 days, the cement shall be Type V, the stone aggregate shall have a maximum diameter of one-half inch, and the slump shall be within a range of 4 to 6-inches. Use stiffer mix or other measures as approved for near vertical joints. Add 1.5 pounds per cubic yard FIBERMESH I synthetic fiber reinforcement per manufacturer's instructions. **(The grout will receive color additive of _______)**

PART 3: EXECUTION

3-1 TYPE I AND TYPE II BEDDING PLACEMENT: For in-situ fine grained soils a layer of Type II bedding shall be placed on top of a layer of Type I bedding. For in-situ coarse grained soils only a layer of Type II bedding is required. Bedding thicknesses shall be as follows:

Riprap Type	Minimum Bedding Thickness (Inches)						
	Fine Grained Soils						Coarse Grained Soils*
	Type I		Type II		Total		Type II
VL, L	4	+	4	=	8		6
M	4	+	4	=	8		6
H	4	+	6	=	10		8
VH	4	+	6	=	10		8

* 50% or more by weight retained on the #40 sieve.

At the Contractor's option a 12-inch layer of Type II bedding may be substituted for the combination layer of Type I and Type II bedding over in-situ fine grained soils. Substitution of one layer of Type II bedding shall not be permitted on the face of drop structures.

3-2 RIPRAP: Excavate for placement of rock riprap lining as indicated. Remove all soft, yielding material; replace with suitable on-site material; compact to smooth firm surface. Machine-place stones into position following details indicated. Arrange as necessary by use of gradall or multi-prong grapple device or hand to interlock and form a substantial bond. Dumping and/or backhoe placement alone is not sufficient to ensure proper interlocked placement. Basic procedure will result in materials that are d_{50} and larger flush to the top surface with faces and shapes matched to minimize voids. Surface grades will be a plane or as indicated, but projections above or depressions under the average surface plane more than 20% less of the rock layer thickness will not be allowed. The average surface plane is defined as the plane where 50% of the tops of rocks would contact. Voids will be filled with a well graded mixture of the remaining material that is securily locked between the larger stone. It is essential that the material between stones not be loose or easily displaced by flow. The remaining stone will also be used to provide a subgrade that will arrive at a proper grade for the surface stone. The stone will be consolidated by the bucket of backhoe or other means that will cause interlocking of the material. The stream side of the riprap is to be uniform and free from bulges, humps, or cavities. All rock is to be placed in a dewatered condition beginning at the toe of the slope or other lowest point.

3-3 COVER STONE: Excavate for placement of the cover stone later as indicated. Remove all soft, yielding material; replace with suitable on-site material; compact to smooth firm surface. Place cover stone on an underlayer of riprap and bedding as shown on the Drawings. Cover stone shall be individually placed in a manner to avoid displacing underlying materials or placing undue impact force on the underlying materials. Each stone shall be covered to essentially the final position by the use of a multi-prong grapple device or suitable equipment for handling material and, if necessary, the stone shall be picked up and repositioned. Dragline buckets and skips shall not be used for placement of cover stone. Placement shall begin at the bottom of slope. Moving stone by drifting or manipulation down the slope will not be permitted. Cover stone shall not be dropped from a height of greater than 1 foot. Stones in their final position shall be oriented such that minimum dimension is parallel to the slope with the flatter side located at the bottom. Adjacent stones shall be set in contact with each other so that the interstices between adjacent stones shall be as small as the character of the stone will permit. The underlying riprap shall be covered, rock to rock contact, one stone deep, as shown on the drawings. It should be anticipated that rehandling of individual stones after initial placement will be required to achieve required slopes, grades, elevations, and position. A tolerance of plus or minus 0.5 foot from the indicated grade, slope, and elevations shown on the drawings will be allowed in the finished surface. To adjust the finish surface and the cover stone, the underlying riprap thickness shall be adjusted. After the cover stones have been placed and approved by the Engineer, additional underlying riprap shall be placed in the voids of the cover stones.

3-4 GROUTED ROCK: Excavate for placement of rock layer as indicated. Remove all soft, yielding material; replace with approved material; compact to smooth firm surface. Placement methods will minimize disturbance of the subgrade. Machine-place stones into position following details indicated. Starting at the lowet point, generally place rocks in stepped fashion with the bottom of the uphill rock below the top of the down hill rock by half the height of the rock minimum. Care shall be taken to remove all fines and smaller rock. Wash the rock free of fines or soil which would affect the grout bond. The concrete grout shall be placed by injection methods by pumping under low pressure, positive displacement methods, through a 2-inch maximum diameter hose to ensure complete penetration of the grout into the rock layer. The voids at the surface, as detailed on the drawings, will not be grouted unless designated. Generally grout will be held down **(6 to 9)** inches. Operator shall be able to stop the flow and will place grout in the voids and not on the surface rock. Clean and wash any spillage before the grout sets. The visual surfaces of the rock will be free of grout to provide a clean natural appearance. A "pencil" vibrator will be used to make sure all voids are filled between and under rock. The intent is to fill all voids from the subgrade level through the rock layer. In all cases, grout must penetrate to subgrade. The pencil vibrator may be used to smooth the appearance of the surface, but the Contractor shall use a wood float to smooth and grade the grout to drain. The grout mix shall be stiffened and other measures taken to retain the grout in steep locations.

PART 4: MEASUREMENT AND PAYMENT

4-1 TYPE XX RIPRAP: The unit of measurement for payment will be the ton of the type indicated. Measurement will be determined by calculating the average rock sections designated on the drawings. The average rock sections designated on the drawings shall be converted to weight using a factor of 1.8 tons per cubic yard. The Engineer will make corrections he deems appropriate to adjust for wastage, material unutilized, and overplacement. The Engineer may at his sole discretion revise the average sections to reflect modifications he requires and practicalities of approved riprap utilized. The average section for measurement purposes will not include the volume of any bedding materials or any other material except the rock. The work shall include all excavation of subgrade materials, overexcavation of unstable subgrade materials and replacement with suitable material as required by the Engineer, grading of slopes to receive riprap, bedding material, and riprap, including chinking to fill voids as shown on the drawings. Quantities so measured will be paid for at the contract unit price.

4-2 XXXXX INCH GROUTED RIPRAP: The unit of measurement for payment will be the ton. Measurement will be determined by calculating the average rock sections designated on the drawings. The average rock sections designated on the drawings shall be converted to weight using a factor of 1.7 tons per cubic yard. The Engineer will make corrections he deems appropriate to adjust for wastage, material not utilized, and overplacement. The Engineer may at his sole discretion revise the average sections to reflect modifications he requires and practicalities of approved rock utilized. The average section for measurement purposes will not include the volume of any material except the rock. The work shall include all excavation of subgrade materials, overexcavation of unstable subgrade materials and replacement with suitable material as required by the Engineer, grading of slopes to receive rock, toe drains and rock. Quantities so measured will be paid for at the contract unit price.

4-3 COVER STONE: The unit of measurement for payment will be the ton. Measurement will be determined by calculating the average cover stone sections designated on the Drawings. The average cover stone sections designated on the Drawings shall be converted to weight using a factor of 1.8 tons per cubic yard. The Engineer will make corrections he deems appropriate to adjust for wastage, material unutilized and overplacement. The Engineer may at his sole discretion revise the average sections to reflect modifications he requires and practicalities of approved cover stone utilized. The average section for measurement purposes will not include the volume of bedding and riprap placed under the cover stone. The work shall include all excavation of subgrade materials, overexcavation of unstable subgrade materials and replacement with suitable material as required by the Engineer, grading of slopes to receive cover stone, bedding material, underlying riprap, and cover stone, including chinking to fill voids as shown on the drawings. Quantities so measured will be paid for at the contract unit price.

4-4 GROUT: The unit of measurement for payment will be the cubic yard. Measurement will be according to certified tickets from the mixing plant or other approved volume measuring techniques, for all grout placed in accordance with the dimensions shown on the Drawings and accepted by the Engineer. The work will include grout, pumping and injection equipment, vibration, and clean-up.

The Engineer Using This Specification Does So At His Own Responsibility and Should Thoroughly Review All Aspects (Items in Parenthesis Must be Addressed)

END OF SECTION

APPENDIX C

Quantity Summary Tables
for Economic Comparison
of Drop Structures

SRR — Sloping Face, Rock Rip-Rap Type Drops

UDFCD Design

Quantities Summary

Unit Costs:				
Rock "M"	30.00 /ton		Grout	100.00 /cu.yd.
Rock "H"	30.00 /ton		Concrete	300.00 /cu.yd.
Rock "VH"	35.00 /ton		Excavate	2.50 /cu.yd.
Boulders	40.00 /ton		all amounts in dollars	

conversions: 1.8 ton/cu.yd. 27 ft3/cu.yd.

ft3 volumes		Rock	Conc.	Exc.	Total Cost
Hd = 2ft					
Q=500	H	4977	368	13532	$15,300
Q=1500	VH	12073	601	30901	$37,712
Q=3000	VH	22969	920	56341	$69,032
Q=7500	VH	50897	1911	130855	$152,108
Hd = 4ft					
Q=500	H	6200	368	16631	$18,032
Q=1500	VH	14676	601	37272	$44,376
Q=3000	VH	27758	920	67682	$81,257
Q=7500	VH	64025	1911	163563	$185,768
Hd = 8ft					
Q=500	H	12400	737	33262	$36,064
Q=1500	VH	29352	1203	74543	$88,751
Q=3000	VH	55517	1840	135364	$162,513
Q=7500	VH	128049	3822	327125	$371,536
Hd = 12ft					
Q=500	H	18600	1105	49892	$54,097
Q=1500	VH	44028	1804	111815	$133,127
Q=3000	VH	83275	2760	203045	$243,770
Q=7500	VH	192074	5733	490688	$557,304

note: Loose rock drops greater than 4ft are not permitted and are considered as multiples of the 4ft drop cost.

VRR — Vertical Face, Rock Rip-Rap Type Drops
UDFCD Design
Quantities Summary

Unit Costs:	Rock "M"	30.00 /ton		Grout	100.00 /cu.yd.
	Rock "H"	30.00 /ton		Concrete	300.00 /cu.yd.
	Rock "VH"	35.00 /ton		Excavate	2.50 /cu.yd.
	Boulders	40.00 /ton		all amounts in dollars	

conversions: 1.8 ton/cu.yd. 27 ft3/cu.yd.

ft3 volumes		Rock	Conc.	Exc.	Total Cost
Hd = 2ft					
Q=500	M	3849	1171	14156	$22,017
Q=1500	H	8850	1842	32593	$41,189
Q=3000	H	12742	2523	49122	$58,064
Q=7500	H	26472	4922	107574	$117,597
Hd = 4ft					
Q=500	VH	7036	2455	23517	$45,867
Q=1500	VH	12705	3412	44871	$71,714
Q=3000	VH	18294	4653	67676	$100,654
Q=7500	VH	38005	8754	146984	$199,560
Hd = 8ft					
Q=500	VH	14071	4909	47033	$91,734
Q=1500	VH	25411	6824	89742	$143,428
Q=3000	VH	36588	9306	135351	$201,308
Q=7500	VH	76010	17509	293967	$399,119
Hd = 12ft					
Q=500	VH	21107	7364	70550	$137,601
Q=1500	VH	38116	10237	134613	$215,142
Q=3000	VH	54882	13959	203027	$301,962
Q=7500	VH	114014	26263	440951	$598,679

note: Loose rock drops greater than 4ft are not permitted and are considered as multiples of the 4ft drop cost.

SLR3 — Moderate Sloping Large Rock Design
MWE Design
Quantities Summary

Unit Costs:	Rock "M"	30.00 /ton	Grout	100.00 /cu.yd.
	Rock "H"	30.00 /ton	Concrete	300.00 /cu.yd.
	Rock "VH"	35.00 /ton	Excavate	2.50 /cu.yd.
	Boulders	40.00 /ton	all amounts in dollars	

conversions: 1.8 ton/cu.yd. 27 ft3/cu.yd.

ft3 volumes	Rock	Conc.	Exc.	Total Cost
Hd = 2ft				
Q=500	7477	374	19284	$20,889
Q=1500	15286	638	43333	$41,675
Q=3000	28266	984	81564	$75,020
Q=7500	58418	2045	187424	$156,908
Hd = 4ft				
Q=500	12503	413	28454	$32,226
Q=1500	25124	708	61936	$63,847
Q=3000	43637	1092	110364	$109,628
Q=7500	87715	2269	249226	$223,717
Hd = 8ft				
Q=500	25007	825	56908	$64,451
Q=1500	50248	1416	123872	$127,694
Q=3000	87274	2184	220729	$219,256
Q=7500	175430	4538	498452	$447,433
Hd = 12ft				
Q=500	37510	1238	85363	$96,677
Q=1500	75372	2123	185807	$191,542
Q=3000	130911	3277	331093	$328,885
Q=7500	263144	6807	747678	$671,150

GSB2

Grouted Boulder Type Drops
MWE Design
Quantities Summary

Unit Costs:	Rock "M"	30.00 /ton	Grout	100.00 /cu.yd.
	Rock "H"	30.00 /ton	Concrete	300.00 /cu.yd.
	Rock "VH"	35.00 /ton	Excavate	2.50 /cu.yd.
	Boulders	40.00 /ton	all amounts in dollars	

conversions: 1.8 ton/cu.yd. 27 ft3/cu.yd.

ft3	Rock	Boulder	Conc.	Grout	Exc.	Total Cost
Hd = 2ft						
Q=500	0	4184	325	1098	12928	$20,028
Q=1500	789	8372	538	2198	30298	$40,828
Q=3000	2273	14866	866	3902	57475	$73,583
Q=7500	7082	30426	1799	7987	137266	$157,574
Hd = 4ft						
Q=500	0	5373	325	1410	15990	$24,638
Q=1500	789	10510	538	2759	36172	$49,151
Q=3000	2273	18259	866	4793	66676	$86,779
Q=7500	7082	37280	1799	9786	157340	$184,373
Hd = 8ft						
Q=500	0	7564	325	1986	22016	$33,170
Q=1500	789	16873	601	4429	51602	$74,437
Q=3000	2273	24864	866	6527	85006	$112,512
Q=7500	7082	50808	1799	13337	197417	$237,310
Hd = 12ft						
Q=500	0	9756	325	2561	18615	$40,829
Q=1500	789	21336	601	5601	41664	$89,755
Q=3000	2273	31289	866	8213	68867	$134,398
Q=7500	7082	64156	1799	16841	161913	$282,594

BC2	Baffle Chute Drops USBR Design Quantities Summary

Unit Costs:			
Rock "M"	30.00 /ton	Grout	100.00 /cu.yd.
Rock "H"	30.00 /ton	Concrete	300.00 /cu.yd.
Rock "VH"	35.00 /ton	Excavate	2.50 /cu.yd.
Boulders	40.00 /ton	all amounts in dollars	

conversions: 1.8 ton/cu.yd. 27 ft3/cu.yd.

ft3 volumes	Rock	Conc.	Exc.	Total Cost
Hd = 2ft				
Q=500	2002	2196	12715	$29,587
Q=1500	4585	3437	28401	$49,992
Q=3000	8606	5157	49758	$79,116
Q=7500	23219	11085	143871	$182,923
Hd = 4ft				
Q=500	2002	2404	13343	$31,950
Q=1500	4585	3826	30087	$54,470
Q=3000	8606	5814	53046	$86,725
Q=7500	23219	12547	151968	$199,926
Hd = 8ft				
Q=500	2002	2819	14601	$36,678
Q=1500	4585	4604	33458	$63,426
Q=3000	8606	7129	59623	$101,943
Q=7500	23219	15473	168161	$233,930
Hd = 12ft				
Q=500	2002	3234	15858	$41,405
Q=1500	4585	5382	36829	$72,382
Q=3000	8606	8444	66199	$117,161
Q=7500	23219	18398	184354	$267,934

VHB4

Vertical Hard Basin Design
Simplified Design
Quantities Summary

Unit Costs:	Rock "M"	30.00 /ton	Grout	100.00 /cu.yd.		
	Rock "H"	30.00 /ton	Concrete	300.00 /cu.yd.		
	Rock "VH"	35.00 /ton	Excavate	2.50 /cu.yd.		
	Boulders	40.00 /ton	all amounts in dollars			

conversions: 1.8 ton/cu.yd. 27 ft3/cu.yd.

ft3	Rock	Boulder	Conc.	Grout	Exc.	Total Cost
Hd = 2ft						
Q=500	499	3234	749	381	21456	$21,347
Q=1500	1578	5618	1089	864	39897	$37,125
Q=3000	2273	9899	1589	1736	62032	$60,766
Q=7500	7082	21368	3339	4171	131875	$135,898
Hd = 4ft		4 ft				
Q=500	499	4116	1333	485	32564	$31,596
Q=1500	1578	7223	1867	1110	57217	$52,568
Q=3000	2273	12504	2637	2192	86115	$83,279
Q=7500	7082	27473	5332	5363	177022	$182,917
Hd = 8ft		8 ft				
Q=500	499	4900	3092	578	54115	$55,573
Q=1500	1578	8828	4170	1357	89329	$86,327
Q=3000	2273	15891	5745	2786	134646	$133,539
Q=7500	7082	33578	11257	6555	250131	$276,223
Hd = 12ft		12 ft				
Q=500	499	5390	5048	635	80327	$81,246
Q=1500	1578	10433	6684	1604	133110	$123,503
Q=3000	2273	18235	9122	3197	189656	$183,928
Q=7500	7082	39683	17656	7746	342108	$376,528

note: At some locations structures greater than 4ft vertical drop are not permitted and higher drops must be considered as multiples of the 4 ft drop cost.

Drop Structure Evaluation Total Cost Comparison Drop Configurations: Q vs Cost				Present Worth Total Costs Rate i = 5.00 % Life N = 50 years		
	SRR Sloping Rock	VRR Vertical Rock	SLR Large Rock	GSB Grouted Boulder	BC Baffle Chute	VHB Vertical Hard
Q = 500 cfs						
Hd = 2ft	$17,594	$23,545	$21,818	$20,839	$30,820	$19,495
Hd = 4ft	$21,721	$48,504	$33,765	$26,041	$33,623	$29,338
Hd = 8ft	$43,457	$96,702	$67,437	$35,321	$39,244	$58,677
Hd = 12ft	$65,183	$144,880	$101,093	$43,729	$44,848	$88,015
Q = 1500cfs						
Hd = 2ft	$44,325	$44,549	$44,346	$43,027	$52,538	$32,771
Hd = 4ft	$55,480	$77,154	$68,388	$52,949	$58,282	$48,139
Hd = 8ft	$110,960	$153,800	$136,558	$80,437	$69,788	$96,279
Hd = 12ft	$166,440	$230,447	$204,730	$97,956	$81,295	$144,418
Q = 3000cfs						
Hd = 2ft	$82,814	$63,689	$80,846	$78,118	$83,624	$55,028
Hd = 4ft	$105,593	$109,921	$119,269	$94,388	$93,759	$78,222
Hd = 8ft	$211,187	$218,970	$238,101	$124,374	$114,028	$156,443
Hd = 12ft	$316,781	$328,020	$356,934	$150,879	$134,297	$234,665
Q = 7500cfs						
Hd = 2ft	$191,449	$130,093	$172,311	$169,261	$193,323	$120,603
Hd = 4ft	$246,677	$220,515	$248,897	$203,910	$216,592	$170,698
Hd = 8ft	$493,353	$439,362	$496,705	$268,022	$263,150	$341,397
Hd = 12ft	$740,029	$658,208	$744,514	$324,480	$309,708	$512,095
Reference:	UDFCD	UDFCD	MWE	MWE	USBR	COMB

APPENDIX D

Excempt from Bathurst (ref. 4)

Discussing Flow Resistance Relationships

INTRODUCTION

The following pages are excempts from ref. 4. The information from this study more closely describes the flow regime on sloping rock drops. The definition of the terms used are as follows:

d = depth of flow

g = gravitational constant

f = Darcy Weisbach coefficient

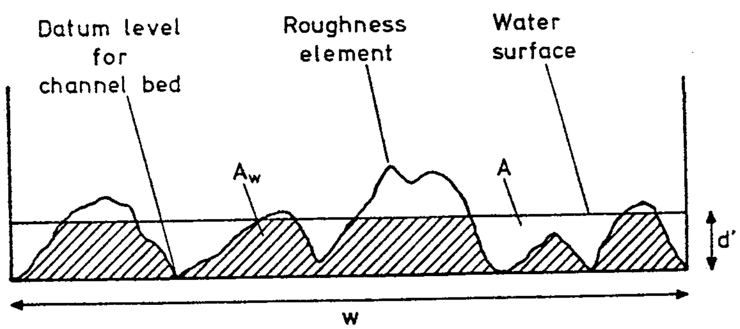
F_r = Froude Number

S = Energy Gradient

S_{50} = median axis of the short dimension of the rock

U = mean velocity of the section

Y_{50} = median size of rock along the cross stream axis



A = flow cross-sectional area

A_w = wetted roughness cross-sectional area

$$A + A_w = wd'$$

A_w / wd' = relative roughness area

The following are excerpts from Bathurst (ref. 4):

SECTION 14 CONCLUSIONS AND RECOMMENDATIONS

An attempt has been made to describe the hydraulics of flow in mountain rivers and to produce a process-based equation accounting for the flow resistance.

Mountain rivers are one form of cobble-bed rivers and are characterized by channel slopes of approximately 0.4 to 10 percent and by relative submergences of less than about 15, corresponding to the regions of large-scale and intermediate-scale roughness. The processes of flow resistance are not the same as those in cobble-bed rivers of lesser gradients and small-scale roughness so the flow resistance equations for those rivers can not be used. Most of the flow resistance is derived from the form drag of the roughness elements and the distortions to the flow around the elements. Consequently a flow resistance equation for mountain rivers has to account both for the processes of fluid mechanics by which the form drag is generated and for the processes of wall geometry by which the combined drag of the elements affects the flow resistance. More specifically the resistance varies with Reynolds number, Froude number, roughness geometry, channel geometry and, where relevant, sediment movement.

Theoretical analysis, supported by the results of the flume study, suggests that, for the range of Reynolds numbers given by $4 \times 10^4 < \bar{U} D_{50}/\nu < 2 \times 10^5$, resistance is likely to fall significantly as Reynolds number increases. However, if there are roughness elements protruding through the free surface, the effect is small by comparison with Froude number effects related to the appearance of hydraulic jumps and the generation of free surface drag. For the bed as a whole, free surface drag decreases as Froude number and relative submergence increase. Once the elements are submerged, Froude number effects related to free surface drag are small but Froude number effects related to standing waves may be important.

The effect of roughness geometry can largely be described by a single parameter, b, the function of effective roughness concentration. This accounts for the variation of the roughness geometry both with depth and with bed material, although it does not make allowance for differing element shapes.

$$b = \left[1.175 \left(\frac{Y_{50}}{w} \right)^{0.557} \left(\frac{d}{S_{50}} \right) \right]^{0.648} \sigma^{-0.134} \qquad (26)$$

Similarly the effect of channel geometry is accounted for by the relative roughness area, A_w/wd', which indicates the proportion of a channel cross section occupied by roughness and thence the degree of funnelling of the flow. For river channels of homogeneous boundary material:

$$\frac{A_w}{wd'} = \left(\frac{w}{d} \right)^{-b} \qquad (22)$$

Based on the analysis of the flume data, the resistance equation for large-scale roughness (b < 0.755) is:

$$\frac{\bar{U}}{(gdS)^{0.5}} = \left(\frac{8}{f} \right)^{0.5}$$

$$= \left[\frac{0.28}{b} \; Fr \right]^{\log (0.755/b)}$$

$$\times \left[13.434 \left(\frac{w}{Y_{50}} \right)^{0.492} b^{\, 1.025 \, (w/Y_{50})^{0.118}} \right]$$

$$\times \left[\frac{A_w}{wd'} \right] \qquad (37)$$

This equation does not apply where Reynolds number effects are significant, where there is bed material movement or where there is a system of standing waves. However, within its range of application the equation seems to work well as long as the various parameters, particularly the roughness sizes and the channel wetted perimeter, are derived or measured as in this study.

In spite of its complex form, Equation (37) contains relatively few parameters and can be applied using a simple iteration procedure (Appendix B). Comparison with independent river data shows that, when based on mean parameters of flow and with semiempirical equations describing relative roughness area and channel width, it can be used to calculate a mean resistance coefficient for a channel reach. Alternatively, in its more general form related to a single vertical through the flow, the equation can be applied to overland flow and to regions of large-scale roughness in channels where there are significant changes in boundary material and depth across a section.

Derivation of Equation (37) proceeded on a semiempirical basis and some of the terms need to be refined. This is particularly true of the parameter describing the free surface drag of elements protruding through the flow. The possible significance of roughness element shape, neglected here, needs to be studied, too. Future research should also be directed towards extending the usefulness of the equation to the region of intermediate-scale roughness which is important in flood studies. This requires that the effects of Reynolds number, sediment movement and standing waves be quantified. In addition it is necessary to find whether the relationship between the resistance function and relative submergence is better represented by a semilogarithmic or a power law.

The brief investigation of bed material movement shows that sediment transport equations developed for sand-bed rivers do not apply to mountain rivers. The flume data suggest that two of the hydraulic factors determining sediment movement are channel slope and bed material characteristics. Other studies, though, show that geomorphic factors, which determine the supply of sediment to the channel, are at least as important and future research should be directed towards identifying these factors.

APPENDIX E

Definition of Symbols

C_i	Impact coefficient
C_w	Lane's weighted creep ratio
d	Diameter of particle
D	Jet Plunge Height at VRR Drop
D_b	Bedding layer thickness
D_g	Grout depth
d_{max}	Maximum size of particle within a gradation
D_n	Drop number
D_r	Rock depth
D_{20}	diameter of particle which 20% of gradation is smaller
d_{50}	Mean diameter of partical (stone)
EGL_m	Energy grade line along main portion of drop
EGL_t	Energy grade line along trickle channel
Elev. Main	Elevation of crest at main drop
Elev. Trickle	Elevation of crest at trickle channel
F	Specific force
F_i	Impact force
F_*	Shields parameter
g	Gravitational constant
h	Height of the wingwalls above the main crest
H_{cw}	Height of cutoff
H_d	Drop height
H_m	Total energy head at the crest of the main drop
H_t	Total energy head at the crest of the trickle channel
H_w	Head on structure for weighted creep ratio, (headwater - tailwater)
K_I or K_i	Isbash constant
L_a	Approach length
L_b	Length of basin
L_d	T
L_f	Length at a vertical hard drop, from the crest wall to the point where the nappe contacts the basin floor inverse

L_h	Weighted creep horizontal length (seepage)
L_v	Weighted creep vertical length (seepage)
n	Mannings roughness
N_f	Froude number = $V/C\ g\ y)^{1/2}$
P	Mass of water
P_c	Packing factor
R	Hydraulic radius
R	Reynolds number
R_c	Critical Hydraulic Radius
R_*	Reynolds number
S	Slope
S_e	Energy Grade Line Slope
S_o	Bed or drop slope (also S used)
SF	Safety factor
S_s	Specific density of sediment
T	Top width
U_b	Velocity of the stone (COE) generally taken as V
U_*	Shear velocity (generally taken as V for flow on the drops)
V	Velocity of flow
y	Depth of flow
y_c	Critical flow depth
y_{cm}	Critical flow depth for main crest of drop
y_{ct}	Critical flow depth at crest in trickle channel
y_f	Vertical fall at drop
y_n	Normal depth
y_p	at a vertical drop, the pool depth under permission from Simons the Nappe just below the crest
Y_1	At a vertical hard drop, the depth of flow at the point immediately below the point where the napped contacts the basin
Y_2	At a vertical hard drop, the tailwater depth required to cause a jump to form starting immediately below the point where the nappe contacts the basin
Z_f	Drop face slope
Z_s	Side inverse slope

α	Angle of bed to horizontal
η	Stability factor
γ	Specific weight of rock
γ	Specific weight of water
ν	Kinematic viscosity
ϕ	Angle of repose
τ	Shear stress
τ_c	Critical Shear Stress (tractive force)