Evaluation of and Design Recommendations for

Drop Structures in the Denver Metropolitan Area

Addendum and Errata

Prepared for:
Urban Drainage and Flood Control District

McLaughlin Water Engineers, Ltd.
December 1986 · Original Report
December 1989 · Addendum and Errata

MWE

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March 14, 1990

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RE: Evaluation of and Design Recommendations for Drop Structures in the Denver Metropolitan Area - Addendum and Errata

Dear Mr. DeGroot:

The three years since our original report have provided the opportunity to test many of the recommendations cited therein. At the same time, the revised Hydraulic Structures Section of the Urban Storm Drainage Criteria Manual (USDCM) was prepared. In the process, refinements and improvements to the report have been completed.

This document is comprised of two parts: Addendum and Errata. The Addendum briefly addresses design refinements and additional information useful in drop structure design. The Errata is mostly minor, although there are a few equations and figures that are important to correct. We have also reissued the References with corrections and numerous additional citations that may be useful.

Sincerely,

William C Taggart
William C. Taggart

Eric Stiles

Enclosures

EAS:mh
85-056.02X1
EAS-1

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SECTION I
ADDENDUM

INTRODUCTION

This discussion highlights advances in technology, useful new references, refinement in analysis, and the experience gained on drop structures since the 1986 MWE report "Evaluation of and design Recommendations for Drop Structures in the Denver Metropolitan Area" by McLaughlin Water Engineers (MWE). Each topic is addressed according to the respective sections of the 1986 MWE report.

The refinements cited herein have been considered in preparation of the revised "Hydraulic Structures" section of the UDFCD criteria manual, to be issued March 15,1990.

SLOPING RIPRAP DROPS - SECTIONS V, X, AND XII

The report analyzed several algorithms for rock sizing on sloping riprap drop, and compared them to parameters measured for sloping riprap drops that had experienced some movement and in some cases near total failure. MWE found that a higher Shield's parameter F* could probably be used for the relatively shallow flow (on a sloping drop for grass lined channels). However, MWE found that a safety factor should be used, and that the approach used by Steven's, 1976 was a very reasonable way of implementing this for sizing riprap. The net effect of this recommendation, coupled with other suggestions for improved construction practices, is that much larger size and thicker layer of riprap would need to be utilized in order to reduce the extent of problems that have occurred.

Dr. Steven Abt of Colorado State University (CSU), 1986 and 1987 published research results concurrent to publication of the 1986 MWE report. Testing of sizes up to 6 inch D50 riprap stability, for flow down sloping faces. Data measured included unit discharge, slope, stone size, interstitial velocity within the riprap, resistance to flow, effects of the flow on the filter blanket, channelization of flow through the riprap, and the effects of duration of flow and riprap gradation. Abt reported that failure occurred with an equivalent Shield's parameter slightly greater than expected using the Shield's diagram. This agreed with Taggart, 1986; Smith, 1975; and Wang, et. al 1985. Abt noted that several methods including U.S. Army Corps of Engineers (COE), Stevens, and the Bureau of Reclamation (USBR)) predicted much higher values, while the new CSU and Stephenson's method gave results that agreed with the previous CSU tests. This may be the result of compensating effects since many of the methods evaluated have applied a low Shield's parameter with a relatively high safety factor (A low Shield's parameter results in a larger rock requirement). For the case of shallow flow, such as at a typical drop structure, a somewhat higher Shield's parameter than 0.06, more like 0.07 to 0.09, should be used.

Abt and Wittler, 1988, reported that after consulting with Stevens, a modification could be taken in the approach to formulation of a safety factor based on rock movement force mechanics. That study recommended an equation which correlated well to observed movement. When compared to Steven's original formulation at a safety factor of 1.1 (and a conventional Shields parameter), Abt found that

Steven's methodology gave results 36% to 56% higher. The new analysis considers the weight component of the adjoining rock on the rock being analyzed. In effect, it substitutes the coefficient of friction between rocks for the angle of repose, which appears reasonable for observations in the field. Nevertheless, the relationships proposed by Abt are very useful.

In general, sizing methods proposed by the 1986 MWE report and Abt will tend to produce similar results. Unfortunately, for drop structures this still results in the need for very large riprap and more expense than other options. Considering the construction difficulties, UDFCD has chosen to recommend other types of drops.

As another footnote, Simons, Li, and Associates (SLA), 1986, performed a study of scour and riprap stability at submerged drops, which may be useful for analysis of sloping riprap drops.

SEEPAGE ANALYSIS- SECTION XII

Flow net and computerized seepage flow and pressure analysis is a clear improvement over Lanes Weighted Creep Analysis because it is much more practical to handle multiple layers, and predict flows and pressures. Lanes Weighted Creep Analysis is given as a minimum approach. With the advent of microcomputers and the numerous software packages available, computerized seepage analysis is preferred.

EFFECTS OF HYDRAULIC JUMP TURBULENT PRESSURE FLUCTUATIONS ON RIGID STRUCTURES SECTION XI AND XII

At about the same time as the 1986 MWE report was issued, research results on turbulent pressure fluctuations were published by Toso, 1986, and Bowers, 1988. These reports documented more clearly that the severe turbulence in a hydraulic jump can pose some special problems often ignored in hydraulic structure design. Turbulence can cause significant positive and negative pressure fluctuations along a rigid structure.

A good example of the problem is illustrated by a situation in which an impervious, rigid sloping drop face is entirely underlaid by a gravel seepage blanket. If the gravel provides a continuous free seepage path to the bottom of the basin or other locations where the jump will occur, the positive pressure fluctuations could be transmitted directly to the area under the sloping face. This condition can destabilize the structure if there is insufficient weight (of water) in the area of shallow supercritical flow to counter the uplift forces. This exact situation caused a major failure of a large dam spillway (Bowers, 1988) and is thought to be a contributing factor to failure in smaller drops.

Toso, 1986, presents a thorough discussion and several laboratory studies of this situation. The data is derived for somewhat higher Froude numbers than is generally encountered in the design of drops for grass lined channels. Until better information is available, it is advisable to review data that is close in range to the site conditions considered in design.

The key parameter is the coefficient of maximum pressure fluctuation $C_{p\text{-max}}$, which is in terms of the velocity head of the supercritical flow jus upstream of the jump:

$$C_{p\text{-max}} = P/(V_1^2/2g) \tag{2-8}$$

where: P = Pressure deviation (fluctuation) from mean (ft),
V_1 = Incident velocity (just upstream of jump (fps),
Y_1 = Incident depth (ft), and
g = Acceleration of gravity (ft/sec^2)

Effectively, C_p is a function of the Froude Number of the supercritical flow. The parameter varies as a function of the downstream distance, X, from the beginning of the jump.

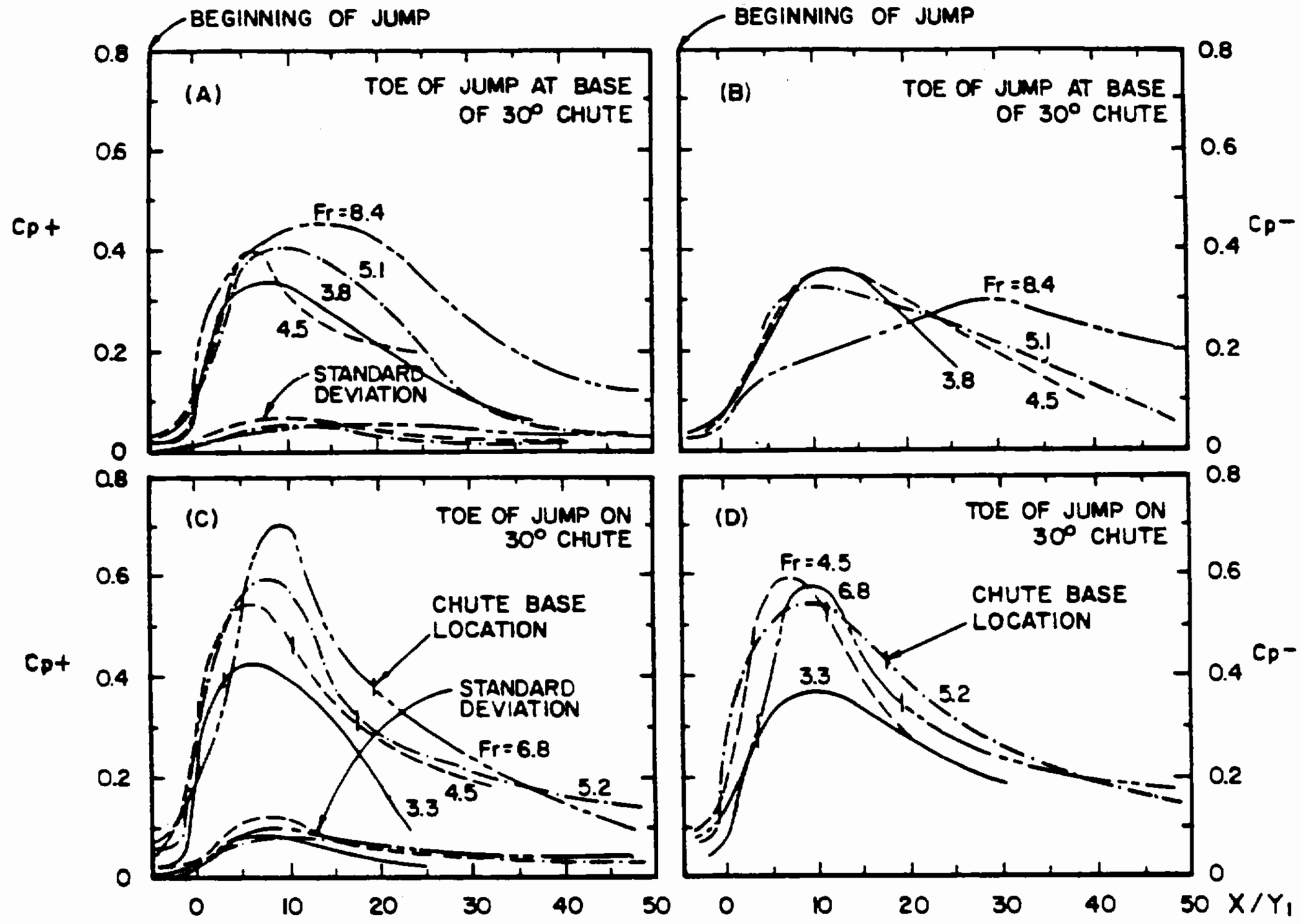
Table 1-1 presents recommended $C_{p\text{-max}}$ positive pressure values for various structure configurations. When the Froude number for the design case is lower than those indicated, the lowest value of C_p indicated should be used for any quick calculations (but do not reduce values on a linear relationship). The values can be tempered by reviewing the C_p graphs given in the reference, a few of which are given here. Note that the graphs are not maximum values but have the mean fluctuation of pressure. The standard deviation of the fluctuations are also indicated, from which the recommended $C_{p\text{-max}}$ values were derived.

TABLE 1-1
NOMINAL LIMIT OF MAXIMUM PRESSURE FLUCTUATIONS
(Adapted from Toso, 1986)

Jump Condition	**Froude Number**	**Suggested Maximum C_p**
0° Slope, Developed Inflow (boundary layer at surface)	3.0	1.0
30° Slope, Toe of Jump at Base of Chute*	3.8	0.7
30° Slope, Toe of Jump on Chute	3.3	0.8*
30° Slope for USBR Basin II	5.0	0.7
30° Slope for USBR Basin III	5.0	1.0

*Velocity head increased by elevation difference between top of jump and basin floor.

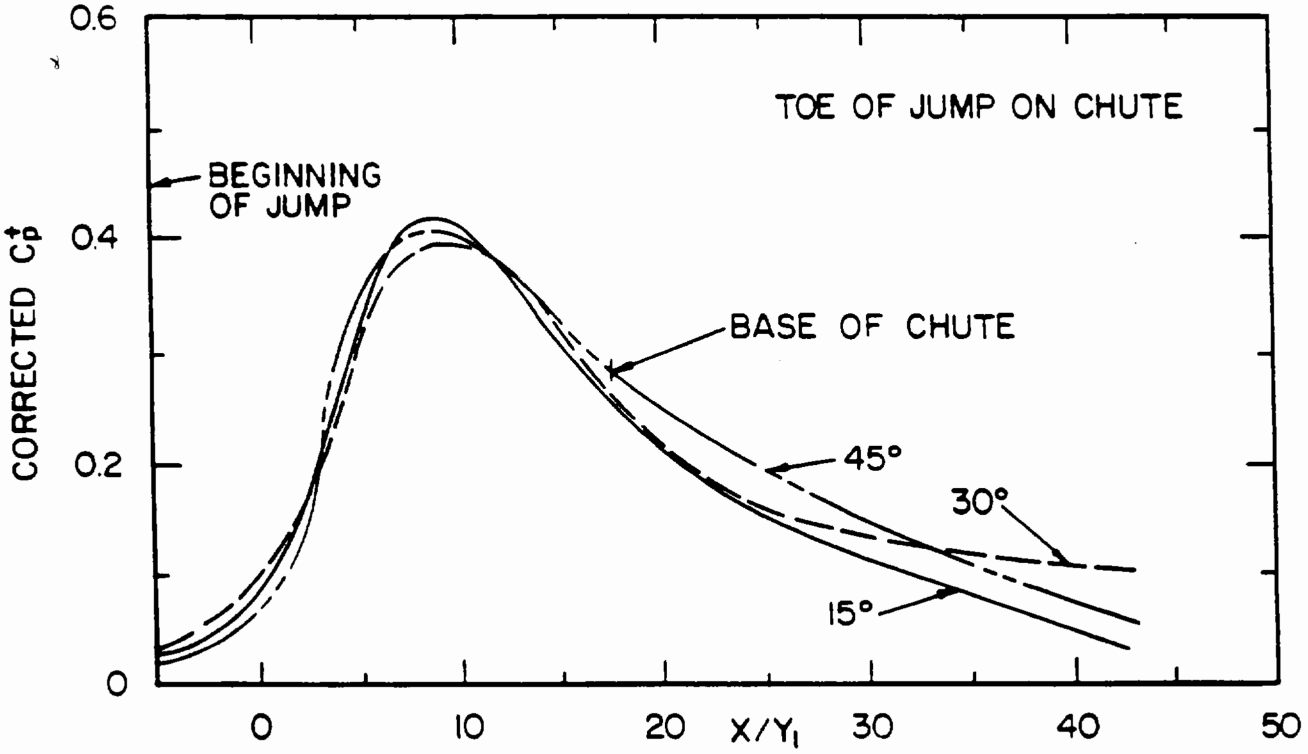
Figure 1-1 illustrates positive and negative pressure fluctuations coefficient, C_p, with respect to location where the jump begins at the toe. Figure 1-2 presents the positive pressure fluctuation where the jump begins on the face slope. Figure 1-3 illustrates how the pressure fluctuation can vary remarkably in USBR Basins II or III.



COEFFICIENT OF PRESSURE FLUCTUATION, Cp AT A HYDRAULIC JUMP

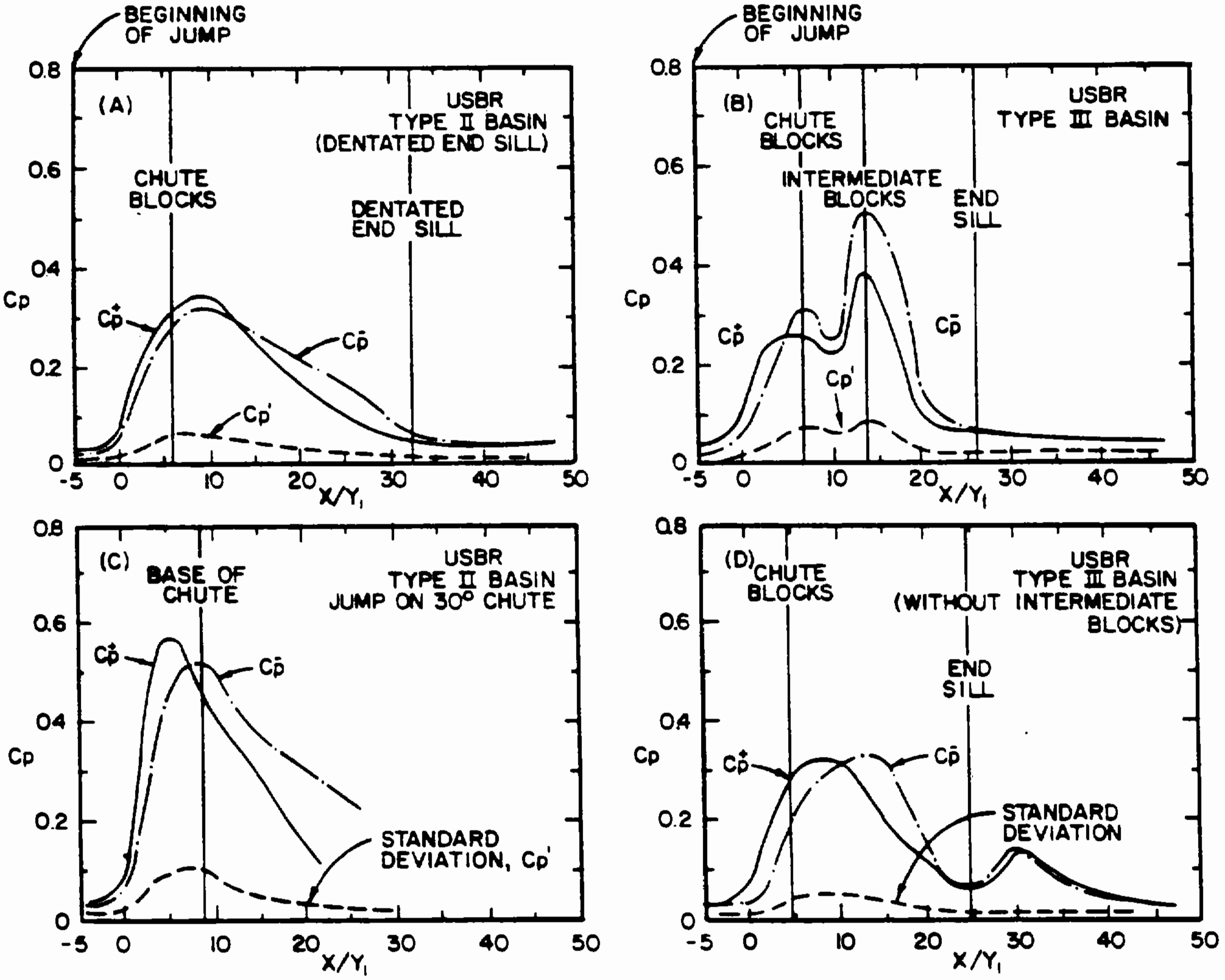
FIGURE 1-1

(Ref., Toso, 1986)



PRESSURE FLUCTUATION COEFFICIENT, Cp NORMALIZED FOR CONSIDERATION OF SLOPE

FIGURE 1-3



COEFFICIENT OF PRESSURE FLUCTUATION, Cp IN A JUMP ON A USBR II OR III BASIN

(Ref., Toso, 1986)

For a typical drop structure where weep drains are provided at the toe and the supercritical occurs at the toe flow, these pressure fluctuations should not be of a great concern. However, when submergence causes the jump to move upstream and the drains discharge to the jump zone, pressure fluctuations could be transferred to areas under supercritical flow and produce a net uplift condition of concern.

OVERALL FORCE ANALYSIS - SECTION XI

The overall force analysis should consider specific points along the drop and the overall drop structure stability including geotechnical and structural stability. The horizontal components are generally small (less than 1 psi) and capable of being resisted by the strength of the grouted rock or reinforced concrete. When problems occur, they are generally a result of net vertical instability at Point 3 and/or seepage uplift pressure problems. It has been concluded that a weep drain system and/or a large toe drain is generally needed with evaluation of the hydraulic jump and submergence problems discussed previously.

The critical design factors are seepage cutoff and relief, and pressure fluctuations associated with the hydraulic jump. Safety factors usually have some comparison of stresses occurring versus stress allowable. With the denominator fixed, various safety factors that have been reported are comparable. In the 1968 MWE report, a safety factor approach was suggested based upon the sum or forces down divided by the sum of forces up. Since the forces up can vary from situation to situation, the resultant safety factors are inconsistent. After further study, a more meaningful approach has been developed whereby a safety allowance is required at any point and under all flow conditions up to and including the 100 year flood. Generally a 30 pound net downward safety allowance should be provided, and 60 pounds is much preferred.

For grouted rock and concrete, this method will generally reduce the thickness requirements indicated in the 1986 MWE report. This is particularly true for higher discharges and depths. Therefore, Figure XI-2 should be replaced with the simpler 30 pound net force guideline.

GROUTED SLOPING BOULDER DROPS - SECTION XII

Table 1-2 presents the minimum guidelines for grouted rock layer thickness based upon the application of the above safety allowance approach.

TABLE 1-2
MINIMUM DESIGN THICKNESS CRITERIA GROUTED SLOPING BOULDER DROPS

Design Parameter	Drop Height 3 foot or less	Drop Height Greater than 3 feet
Uniform Rock Size - Minimum Dimension	1.5 foot	2.0 foot*
Minimum Grout - Thickness	1.0 foot	1.5 foot*

*May use 1.5 rock and 1.0 foot grout for flow depths upstream of crest (normal depth) less than 3 foot.

VERTICAL RIPRAP DROPS - SECTION XII

The design method presented in the 1986 MWE report is based on original research by Smith and Strang, 1967, later extrapolated by Stevens, 1981. Although this work is still applicable, it has been climated from the revised USDCM Hydraulic Structures section in favor of a simplified guideline.

Since 1986, UDFCD has reduced the maximum allowable vertical drop height to 3 feet for safety reasons. To address submergence problems, MWE reviewed several references (Linden, 1963; Urbonas, 1968; the COE, 1970; Corry, 1975; Little, 1981 and 1982; and SLA, 1986. The simplified guidelines as presented in the revised structures section of the USDCM, are based on the original work by Smith and Strange amended to consider submergence and function within the UDFCD maximum channel flow parameters.

BAFFLE CHUTE DROPS - SECTION XII

Refinements are now available regarding back water effects produced by the first row of baffle blocks which protrude into the upstream flow area in the standard USBR design. The Fujimoto entrance, also developed by the USBR, is a modification that can be used to reduce such effects. This and other information is presented in the revised Hydraulic Structures section of the USDCM.

NOTES REGARDING THE REVISED HYDRAULIC STRUCTURES DESIGN CRITERIA

The theoretical background information presented in the 1986 MWE report has served as a basis for developing the more simplified design criteria currently included in the 1990 revised Hydraulic Structures section of the USDCM. Graphical relationships, are now provided which give the basic drop crest configuration and channel parameters as a function of discharge which will result in performance at allowable maximum flow conditions. The crest transition configuration is essential to control the approach velocity acceleration while simultaneously preventing backwater depth from becoming excessive.

There is a balance between the crest shape chosen, upstream channel stability, and the configuration downstream of the drop which will result in optimal or reasonable energy dissipation. Further, there is usually a single configuration of drop crest, upstream channel slope and base width which will result in channel performance at the maximum flow conditions allowable by the UDFCD grass lined channel criteria.

Note that the simplified methods in the revised criteria do not specifically address hydraulic performance in the trickle zone, where higher unit discharge and energy will occur. The flow characteristics in the trickle channel should be reviewed. Figures in the revised criteria provide basic drop structure layout guidelines, while the remaining design criteria are provided in the specific sections for each type of drop structure.

These relationships provided a good starting point for design. The designer should recognize the high likelihood of erosion and stability problems with channels that perform at the maximum allowable channel conditions.

RESEARCH NEEDS - SECTION XV

Items 51,52,53 and 55 in the original 1986 remain as valid research and monitoring concerns. Basically, they relate either the trickle channel an its incorporation in the drop and resulting effects and control measures upstream and downstream, or with seepage and other surface related hydraulic pressures under the structure. In any suspected or real problem situation, these factors should be monitored and analyzed.

SECTION II
ERRATA

INTRODUCTION

The following corrections should be made to the original 1986 report. The following is organized by section numbers in the report. **Bold labeled changes are important.**

Table of Contents

page TOC-5, Section XI Grouted Rock Review,
change "Impact Force" to
"Impact and Drag Forces"

and after "Frost Heave" add
"Dynamic Pressure Fluctuations . . . . XI-4"

page TOC-7, Change Appendix A title to
"Amended and Corrected References"
and change Appendix E title to
"Corrected Definition of Symbols"

page TOC-11, delete
"XI-2 Design Guidelines for Grout Thickness . . . . XI-2"

page TOC-12, add
"XI-I Minimum Design for Sloping Grouted Boulder Drops . . . . XI-2"

Section III

page III-1, 3rd paragraph, 4th line: change "acceptable" to
"acceptable".

page III-1,4th paragraph, 2nd line: change "applications" to
"applications".

page III-1, 5th paragraph, 5th line: change "Derrck" to
"Derrick."

Section V

See Discussion of new riprap studies in Addendum Section I.

page V-3, 2nd paragraph, first line: change "boulders" to
"boulder".

page V-7, 3rd paragraph, 2nd line: change "occurs" to
"occurs".

page V-8, 5th paragraph, Revise 2nd sentence to read:
"Simons reports success using a well graded riprap mixture that includes sizes down to the equivalent of bedding material. A single thick layer of this material is used for bank riprap, rather than multiple layer of riprap and bedding."

page V-9, 3rd paragraph, 6th line: change "thru to through".

Section VI

page VI-5, 3rd paragraph, first line: insert
"is" after the word rock, and delete "is" after the word larger.

page VI-9, Figure VI-9, note that the photograph has been printed upside down.

Section VII

page VII-1, 2nd paragraph, 4th line: change "Bureas" to
"Bureau's".

Section IX

page IX-1, first paragraph, 4th line: insert the following phrase after the phrase "by the":
"surface and groundwater"
and change "interdependancies" to
"interdependencies".

Section X

See discussion of new riprap studies in Addendum Section I.

page X-2, first paragraph, last line. After reference "47" add
",69".

page X-4, next to last line, change "water" to
"stone".

page X-5, change equation X.3 and X.4 to read

$$R_* = U_* d/8 \qquad \text{X.3}$$

where

$$U_* = (qRS)^{1/2} \qquad \text{X.4}$$

= **Kinematic viscosity**

page X-6, Figure X-2, change phrase "umad (ref 65)" to
"Samad (ref 42)".

page X-10 and X-11, the last heading and paragraph on page X-10 should be moved ahead of heading on page X-11 which reads:

"Original Tractive Force Logarithmic Profile".

also add the following phrase:

> **"The authors of this drop structure study have found this to be a very useful reference for channel riprap sizing, within the limitations cited and realizing that the methodology will not allow analysis of currents at disparate direction from a sloping bank or in the situation of shallow flow, such as drop structures".**

page X-11, after equation X.14 and the phrase "mass density" add the phrase
"of water".

page X-13, change equation X.16 and X.17 to read:

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

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

page X-14, first paragraph, 6th line, change "Determinstic" to
"Deterministic".

page X-21, Equation X.22 and in definition of symbols following change "H" to "H_d".

page X-22, first paragraph, 2nd line, change "alterntive" to "alternative".

pages X-37 through X-40, In the last caption line of each figure change "Notes" to "Noted".

Section XI

page XI-2, Delete Figure XI-2 and Insert Table XI-1 as explained in the Addendum Section.

TABLE XI-1
MINIMUM DESIGN GUIDELINE FOR GROUTED SLOPING BOULDER DROPS FOR GRASS LINED CHANNELS

Design Parameter	Drop Height 3ft. or Less	Drop Height Greater than 3ft.
Uniform Rock Size - Minimum Dimension	**1.5 ft.**	**2.0 ft.***
Minimum Grout - Thickness	**1.0 ft.**	**1.5 ft.**

*** May use 1.5 ft. rock and 1.0 ft. grout for upstream normal flow depth less than 3 ft.**

Note that the overall drop structure dimensions such as basin length, or basin depression depth are determined by applying water surface profile or specific force calculations. These hydraulic calculations may be simplified to a unit flow basis as described on page X-27.

page XI-3, change equation XI.1 to read:

$$= \quad y\ Se \qquad \text{XI-1}$$

page XI-3, 3rd paragraph, change heading to read

"Impact and Drag Forces"

and replace the paragraph and equation XI.2 with:

"Water flowing down the drop will directly impact any abrupt rock faces or concrete structure projecting into the flow. Technically this is a type of drag force which can be estimated by equation XI.1. Also, the user should compare calculated drag force results with the forces shown in the revised structures section for baffle chute blocks. A drag coefficient, Cd, of 0.333 was assumed in Equation XI.2 for the drag force of the shape projecting into the flow: The assumption made under previous paragraph allows the rock to project 25% of the grout thickness, Dg.

$$F_D = C_D\, P\, (V^2/2)\, (0.25\ Dg) \qquad \text{XI.2}$$

Note that this drag is similar to the shear stress discussed earlier, but it differs in that it is a drag related to the sudden projection into the flow. Impact force caused by debris or rocks, is more difficult to estimate because of the unknown size, mass and time elapsed while contact is made. Therefore it is recommended that a conservative approach be taken with regard to calculating water impact (drag force) which generally will cover other types of impact force. Specialty situations where impact force may be significant must be considered on an individual basis."

page XI-4, add after the 3rd paragraph

Dynamic Pressure Fluctuation

Refer to addendum for discussion.

page XI-4, insert below 4th paragraph,

"Refer to addendum for discussion of safety factor and recommendation to use a minimum surplus force (weight) as a more meaningful and practical approach."

page XI-4, 5th paragraph, replace last sentence with:

With the toe drain provided, the analysis illustrated that the design would be stable with a downward surplus force of no less than 30 pounds if the criteria in Table XI-1 is satisfied.

page XI-4, 6th paragraph, first line, replace "Figure XI-2" with

"Table XI-1".

page XII-1, 3rd paragraph, insert at the end of the first sentence: "

", and Smith (ref. 69)."

page XII-6, In step (2), correct equation XII.1 to replace "H" with
"H_s".

note that the equation is usually expressed differently;
and after "where C_w = weighted creep ratio" insert

H_s = Differential head across the seepage path. Note that there may be several critical seepage paths such as from the upstream water surface to the water surface over the toe drain, or from the downstream tailwater to the water surface over the toe drain.

page XII-7, 2nd paragraph, first line, change "lowered" to
"increased".

page XII-9, Insert at top of page

For many UDFCD drops in grass lined channels, this methodology is at the limit of applicability because of submergence effects and the extent of extrapolation. This is also true for other methods, several of which require more submergence before they apply. See discussion in addendum.

page XII-9, step h, 5th line, insert after C.D. Smith
"ref.(69)".

page XII-10, Figure XII-1, add to the profile

the vertical dimension "d_2" which is the difference between the tailwater and the basin floor. Add the equation

$$d_2 = Y_2 + B$$

page XII-15, at top of page insert:

"Please see addendum for recent research and development, which compliments the approach

page XII-20, replace step d with:

d. Grout thickness, Dg is determined based upon a net minimum downward surplus force of 30 pounds, and 60 pounds is generally preferable. Table IX-1 presents a guideline and minimum criteria.

page XII-23, add to step a:

60 cfs/foot can be exceeded but results in an impractical application to grass lined channels.

page XII-28, Equation XII.7
replace "h" with "y"
and add the sentence:

Where Y_f is the vertical fall from the crest to the floor of the basin in the particular zone.

page XII-30, Figure XII-30,

plan view, on left side where trickle channel width is labeled "$3b_t$" replace with "b_t", and on right side of plainview add a note which will point to the widened rock zone along the trickle channel downstream of the main stilling basin:

"Additional rock protection zone along trickle channel based on basin length in trickle zone."

page XIII-7, Table XIII-4, footnote, replace "27 ft.3/cu.yd." with
"27 cu.ft./cu. yd."

page XV-4, item 18, 3rd line replace (ref. 4) with
"(ref. 43).

Note: Need to be consistent either continue the line after the location or move to new line at all page number corrections.

page XV-6, item 32, 2nd line delete ref. 41.

page XV-10, item 51, 7th line, delete "(ref, 4, 24, 25)".

APPENDIX A
AMENDED AND CORRECTED REFERENCES

1. Aisenbrey, A.J., R.B. Hayes and J.H. Warren and D.L. Winsett and R.G. Young, Design of Small Canal Structures, U.S. Department of the Interior, Bureau of Reclamation, 1974.

2. Anderson, A.G., "Tentative Design Procedure for Riprap - Lined Channels - Field Evaluation", University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Project Report No. 146 prepared for Highway Research Board National Academy of Sciences, 1973.

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10. Chow, Ven Te, Ph.D. Open-Channel Hydraulics, McGraw-Hill Book Company, New York, N.Y., 1959.

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15. U.S. Department of the Army, Corps of Engineers, "Stability of Riprap and Discharge Characteristics, Overflow Embankments, Arkansas River, Arkansas", Technical Report No. 2-650, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, 1964.

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18. Donald H. Godi and Associates, Inc., Guidelines for Development and Maintenance of Natural Vegetation, Drainage and Flood Control District, 1984.

19. Hughes, C., Rock and Riprap Design Manual for Channel Erosion Protection, University of Colorado. Prepared for U.S. Forest Service, Rock Mountain Forest and Range Experment Station, Grant No. 16-525-CA, 1976.

20. Hsu, En-Yun, "Discussion on Control of the Hydraulic Jump by Sills", by John W. Forster and Raymond A. Skrindge, Transactions American Society of Civil Engineers, Vol. 115, pp. 988-991, 1950.

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22. Lederle Consulting Engineers, West Harvard Gulch Rehabilitative Improvements, Engineering Report on Drop Structure Alternatives, Urban Drainage and Flood Control District, 1985.

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APPENDIX E
CORRECTED DEFINITION OF SYMBOLS

A	Area (subscripts as shown in figures)
A_p	Total projected area of piers normal to flow in square feet
B	Basin depth below downstream channel
b_1	Channel base width upstream and downstream of drop
b_2	Channel base width at the drop crest section
b_t	Trickle channel width
B	Basin depth below downstream channel
C	Coefficient relating to superelevation of water surface that occurs at a bend
C_d	Drag force coefficient
$C_{p\text{-max}}$	Coefficient of maximum pressure fluctuationns from mean pressures level in a hydraulic jump.
C_p	Coefficient of mean pressure fluctuations from mean pressure levels in a hydraulic jump
C_W	Lane's weighted creep ratio
D_b	Bedding layer thickness
D_g	Grout depth
D_n	Drop number
D_r	Rock depth
d_s	Depth of scour below drop of outfall
d_2	Depth of basin tailwater = $Y_2 + B$
d_{50}	Mean diameter of particle (stone)
D	Height of fall to basin = $H_d + B$
EGL_m	Energy grade line along main portion of drop
EGL_t	Energy grade line along trickle channel through a drop
El_c	Water surface elevation of critical depth at the crest of a drop
El_m	Elevation of crest of a drop at main channel invert
El_t	Elevation of crest of a drop at trickle channel invert
F	Specific force
F_D	Drag Force (for projecting boulder)
F_i	Impact force
F_j	Impact force of flow jet
F_m	Momentum force
$F_{\bullet}$	Shields parameter

g	Gravitational constant = $32.2\ ft/5^2$
h	Height of the wingwalls above the main crest
H	Height of baffles for baffled drops
H_{cw}	Height of seepage cutoff
H_d	Drop height
h_L	Head loss
h_1^*	Total backwater in feet
H_m	Total energy head at the crest of the main drop
H_s	Differential head, usually at a drop; the difference between the upstream water surface (normal depth) to the downstream tailwater, or the head difference between analysis points (e.g. to point of supercritical flow minimum depth)
H_t	Total energy at the crest of the trickle channel
H_w	Head on structure for weighted creep ration, (headwater-tailwater)
h_V	Velocity head
j	A_p/A_{n2}
K	Backwater coefficient for bridges
K_b	Base curve coefficient, part of K
K_i or K_I	Isbash constant
K_p	Incremental backwater coefficient
K^*	Total backwater coefficient
L_a or L_A	Approach length for upstream and rock protection
L_b or L_B	Length of basin
L_d or L_D	Length at a vertical hard drop, from the crest wall to the point where the flow nappe contacts the basin floorinvert
L_f or L_F	Length of the drop face for a sloping drop
L_j	Length of the hydraulic jump (approximately 6 Y_2)
L_{tu}	Length of channel width transition upstream of the drop crest
L_{td}	Length of channel width transition downstream of the drop toe
L_H	Weighted creep horizontal length (seepage)
L_V	Weighted creep vertical length (seepage)
M	Bridge opening ratio, flow which can pass unimpeded through constriction to total flow in channel
n	Manning roughness coefficient
N_f	Froude number $V/(gy)^{1/2}$
P	Maximum pressure fluctuation at a given location within a hydraulic jump
Q	Discharge in cfs
q	Unit discharge = yV at a given point, in cfs/ft
q_m	Unit discharge in the main channel at drop = $q^{1/2}\, y_{cm}{}^{3/2}$
q_t	Unit discharge in the trickle channel at drop = $q^{1/2}\, y_{ct}{}^{3/2}$
R	Hydraulic radius

r	channel centerline radius of curvature
S	Slope
S_e	Energy Grade line Slope
SF	Safety facotr (with regard to riprap)
S_o	Bed or drop slope (also S used)
S_s	Density of sediment or rock
T	Top width of flow in the channel
U_b	Velocity on the slope (COE) generally taken as V average
U_*	Shear Velocity
V	Velocity of flow in feet per second
W	Width
y	Depth of flow
y_c	Critical flow depth
y_f	Vertical fall at a drop
y_{cm}	Critical depth at a drop in the main channel
y_{ct}	Critical depth at a drop in the trickle channel
y_m	Minimum depth on face of sloping drop (See Ref. 25)
y_n	Normal depth
y_p	At a vertical drop, the pool depth under the nappe just below the crest
Y_{tw}	Actual tailwater depth present downstream of the drop
Y_1	At a vertical hard drop, the depth of flow immediately downstream of the point where the nappe contacts the basin, or at the toe of a sloping drop
Y_2	The tailwater depth required to cause a jump to form immediately downstream of the sequent depth location for Y_1
Z	Channel side slope vertical ratio distance
Z_f	Drop face slope
Z_s	Side inverse slope
	Angular variation of sidewall with respect to channel centerline
	Kinetic energy coefficient
	Standing wave front angle
	Correction factor for K_p
	Shear stress on the bed caused by the flow of water
	Specific weight
	Angle of inflow at confluences