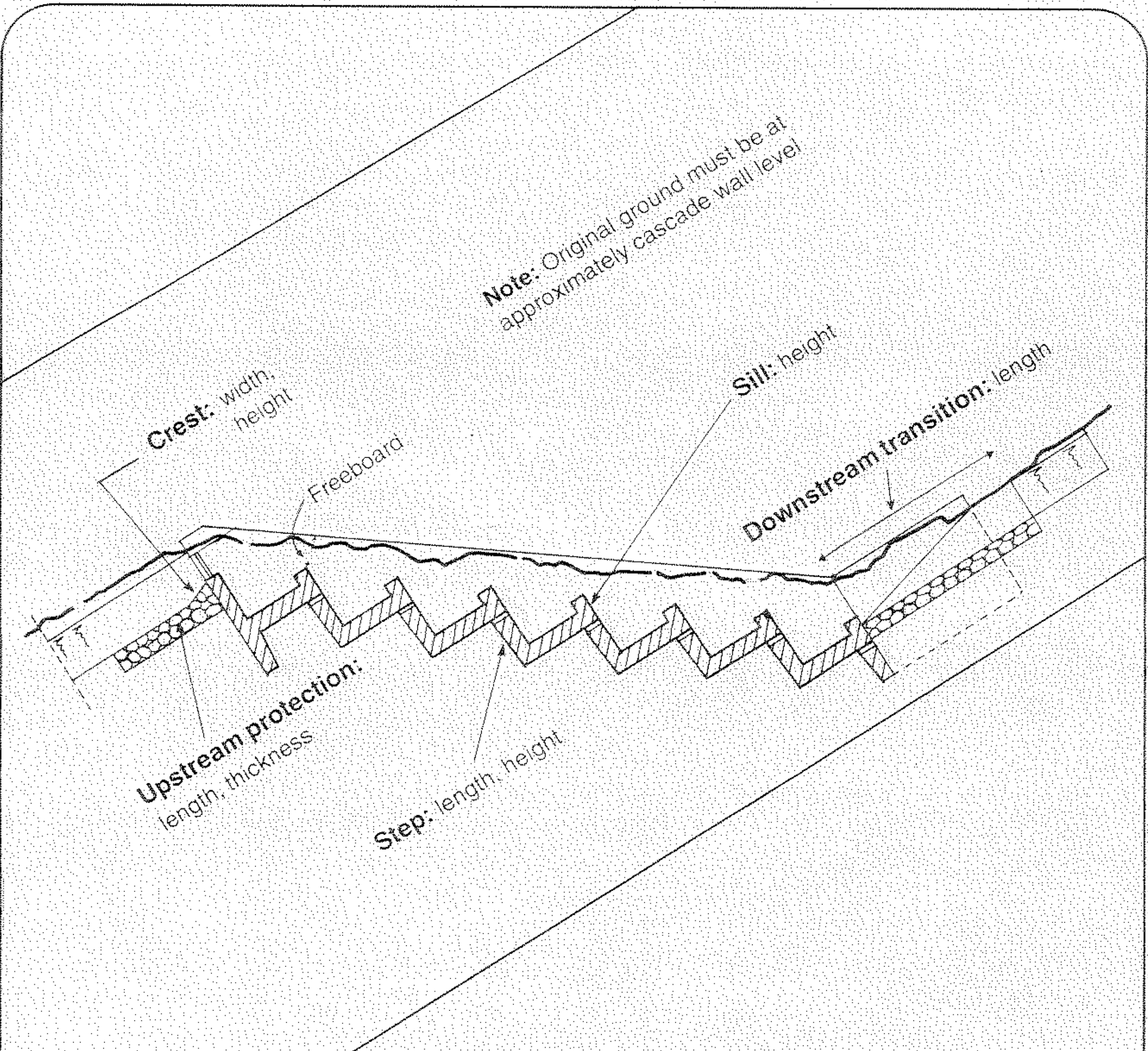
Poverty Alleviation Through Employment Generation in Irrigation Works Programmes

APPROPRIATE DESIGN OF SMALL-SCALE HILL IRRIGATION STRUCTURES



Drop Structures for Hill Irrigation Schemes

NEPAL SPECIAL PUBLIC WORKS PROGRAMME
MANUAL NO. 2

Module No 5

DROP STRUCTURES FOR HILL IRRIGATION SCHEMES

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Why are Drop Structures Required in Canals?

A drop structure is built into a canal to:

- achieve a drop in the water level in the canal,
- check erosion in the canal caused by high flow velocity resulting from steep canal bedslopes,
- raise water levels at offtake locations to design levels so that non-operational offtakes can draw adequate water from the canal.

Range of Drop Heights

Water levels in a hill irrigation canal may need to be lowered by half to several metres, depending on the topography. Drop structures to check erosion of existing canals may need to provide only a few centimetres of drop in the water level, depending on the required correction in the bed slope and the number of drop structures.

Likewise, drop structures for raising water levels at offtakes may need only a few centimetres drop in the water level, depending on the eroded bed level and the design bed level of the canal.

Where to Build Drop Structures?

Drops, particularly large drops, are associated with:

- soil erosion due to high flow velocity,
- soil erosion due to water impact, and
- soil erosion due to turbulence, see Figure 5.1.

The above factors contribute to:

- a progressive deepening of the downstream canal bed,
- progressive backward erosion.

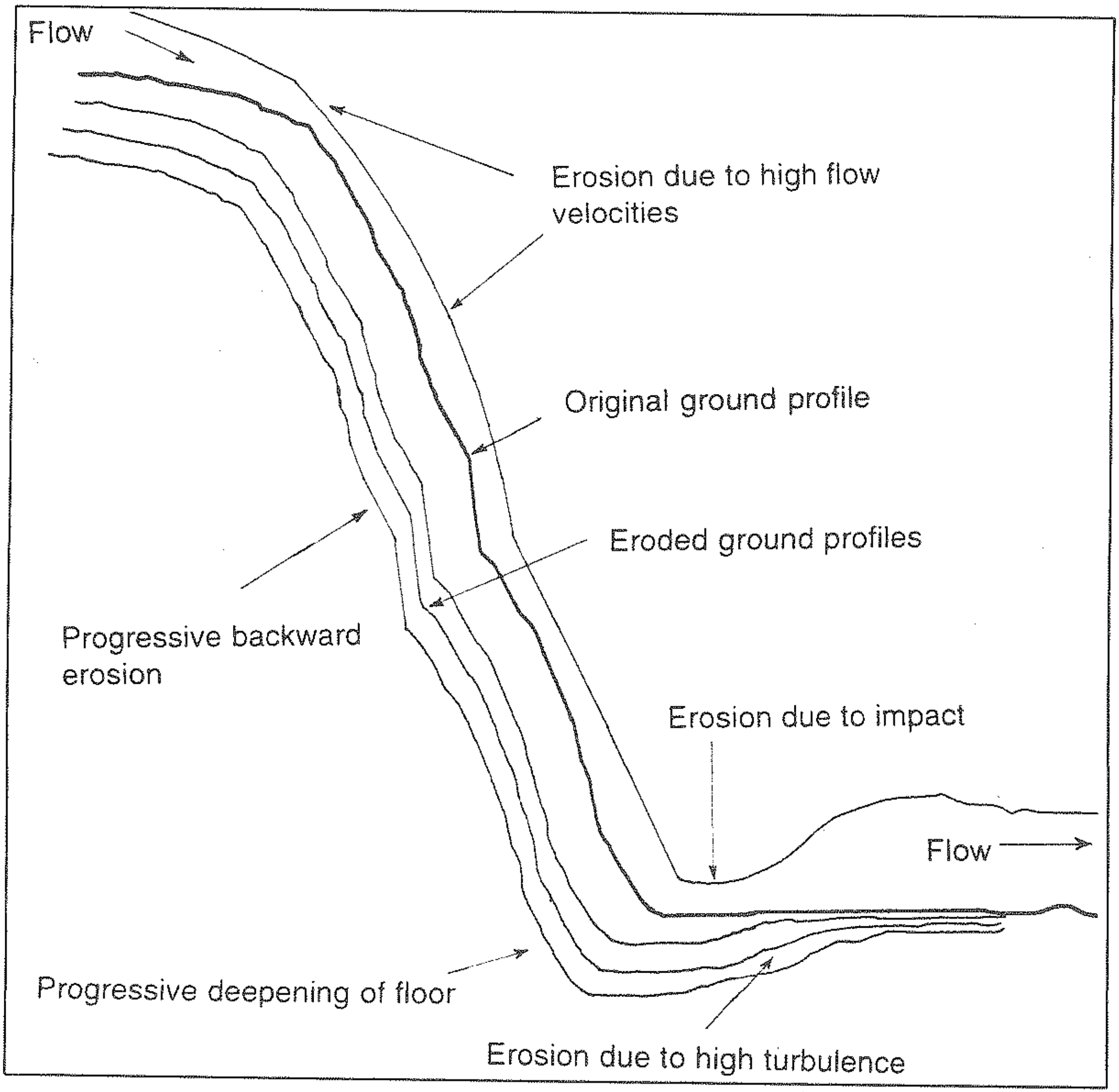
Therefore, to prevent erosion associated with drop structures, it is necessary to locate these structures on:

- firm non-erodible soils, or
- firm rock outcrops in the path of the canal.

When firm non-erodible soils or rock outcrops cannot be found for the location of drop structures:

- their design must minimise the risk of canal erosion, and
- they must be built with strong masonry or concrete for durability.

Figure 5.1
Erosion and Cutting Due to High Flow Velocity, Turbulence and Impact Forces of the Water



Different Types of Drop Structures and Their Suitability for Use in Remote Small/Medium Hill Irrigation Systems

FOUR types of drop structures are suitable for use in irrigation canals:

1. vertical drop (also called straight drop), see Photograph 5A
2. chute drop (also called sloping drop), see Figure 5.2
3. cascade drop, see Photograph 5B, and
4. pipe drop, see Figure 5.3.

For all these drop types it is true that as the drop height increases:

- flow velocities in the structure increase,
- impact forces due to falling water increase,
- impact forces due to water jets increase, and
- abrasive action of the sediment in fast moving water increases.

Therefore, stronger walls and floors are needed to resist:

- erosion,
- impact forces of the water, and
- abrasion.

Furthermore, complex stilling basins will be needed to control turbulence associated with large drop heights.

Photograph 5A
A Vertical Drop Structure in a Masonry Lined Canal

Photograph 5B
A Cascade Drop Structure in Stone Masonry

Figure 5.2
Chute Drop Structure

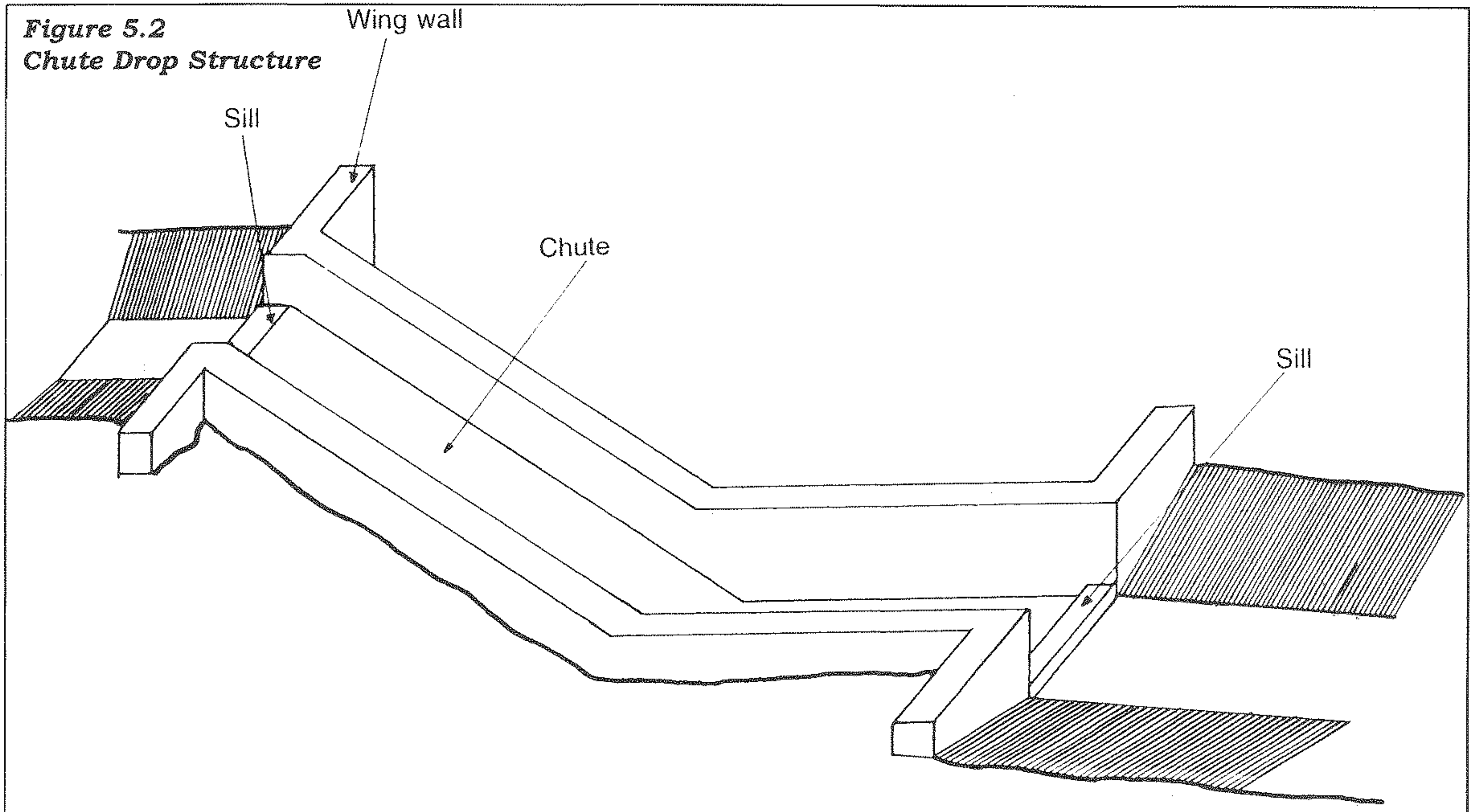
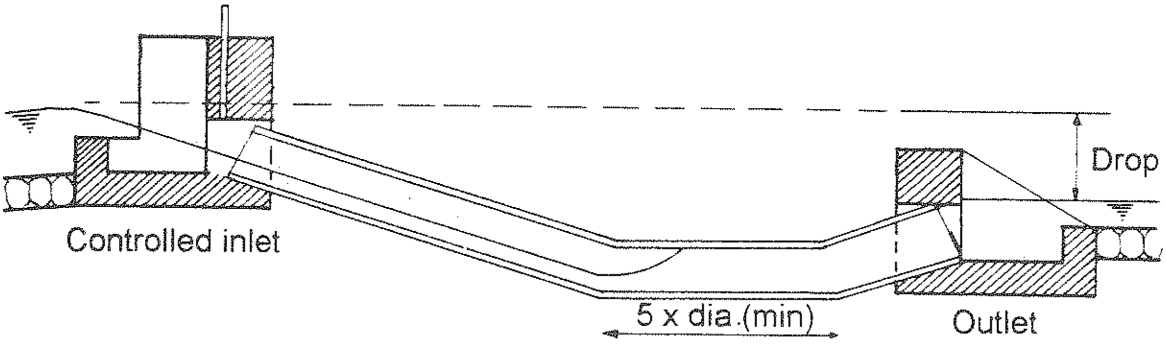
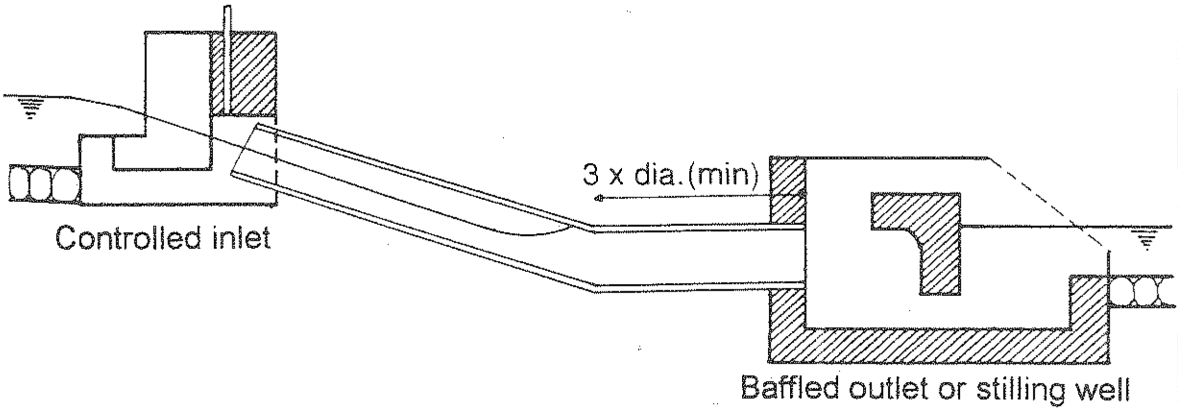


Figure 5.3
Pipe Drop Structure



... with a Simple Box Outlet for Low Flow Velocity



... with a Baffled Outlet for High Flow Velocity

Limitations in Remote Hill Areas

In remote hill areas construction of large drop structures is difficult and undesirable for three main reasons:

- difficulty in construction:
  - good quality construction materials for making the strong walls and floors required for large drop structures are often not locally available,
  - constant construction supervision is difficult due to lack of experienced staff,
  - construction skills for making complex stilling structures in masonry or concrete are not readily available.
- undesirability of heavy excavations:
  - large drop structures require heavy excavation which leads to unstable hill slopes.
- difficulty in maintenance:
  - complex stilling basins are difficult for farmers to repair and maintain.

It is therefore desirable to limit the drop heights to:

- below 2 metres in vertical and chute drops,
- below 4 metres in cascade and pipe drops.

Exceptions to these rules may be considered on a case by case basis.

Basic Hydraulic Principles

The common hydraulic principle in all types of drop structures is the dissipation of EXCESS energy as the water drops from a high level to a low level.

All of the water's excess energy must be dissipated inside the drop structure before the water is allowed back into the downstream canal.

Energy of flowing water can be dissipated by:

- hydraulic jumps,
- allowing the flow to strike baffles, baffle blocks and raised sills,
- using water cushions.

Though several of the different types of energy dissipators shown in Figure 5.4 are more hydraulically effective than the simple hydraulic jump and the raised sill shown in Figure 5.5 such complex designs cannot be adopted in the hills for the following reasons:

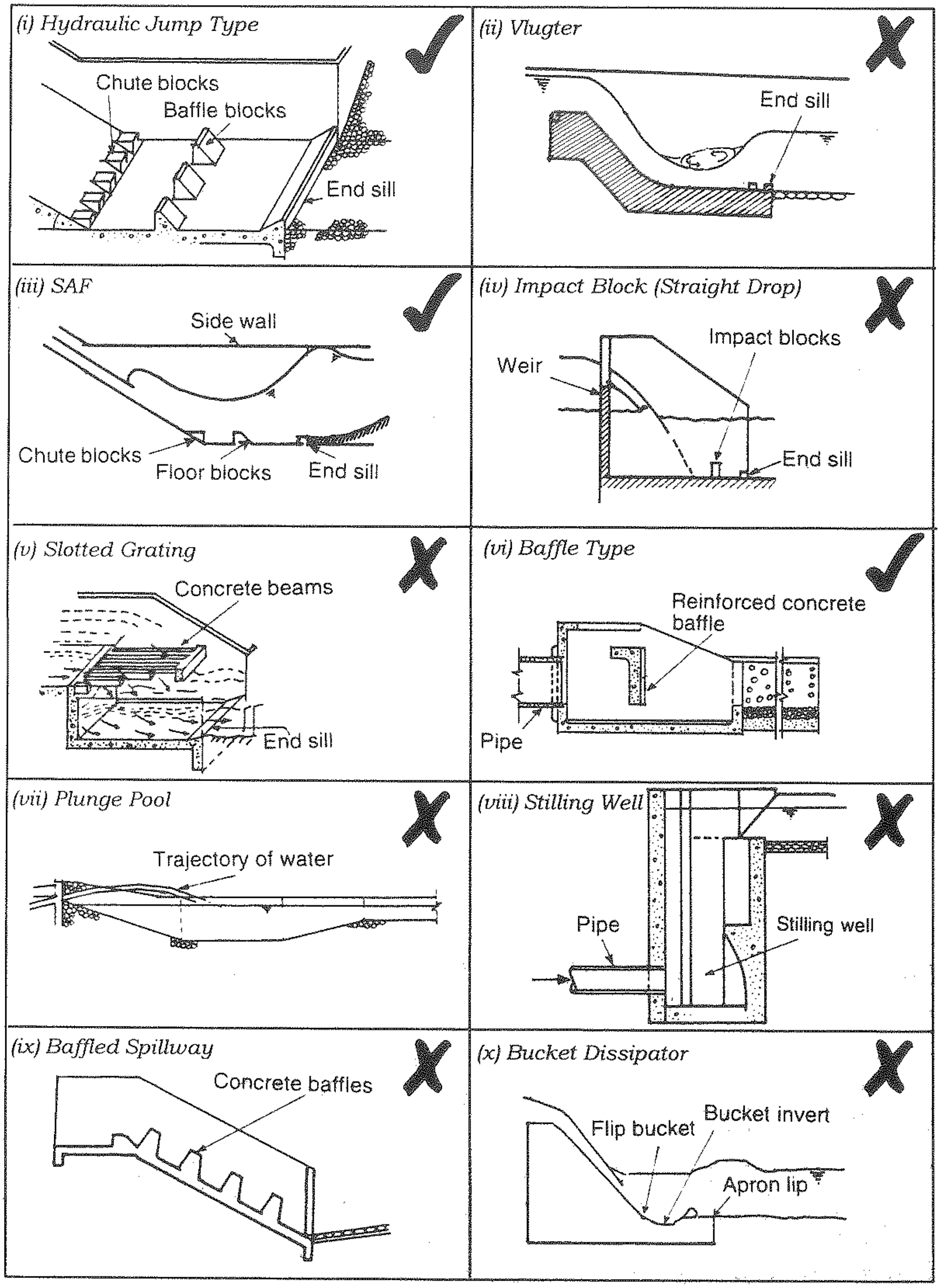
- some are only appropriate for high canal flows,
- some are only suitable for use in the headwork structures of large irrigation schemes,
- all types require very good construction materials and excellent workmanship to be effective and structurally sound,
- repair and maintenance of complex structures is difficult for farmers.

The Most Cost Effective Solution

A simple hydraulic jump, or a combination of a hydraulic jump with one of a raised sill, standing water pools, or cushions, are the most cost effective solutions in the hills.

These cost effective solutions are hydraulically effective when drop heights are restricted.

Figure 5.4
Different Types of Energy Dissipators



(i) Hydraulic Jump Type ✓

(ii) Vlugter ✗

(iii) SAF ✓

(iv) Impact Block (Straight Drop) ✗

(v) Slotted Grating ✗

(vi) Baffle Type ✓

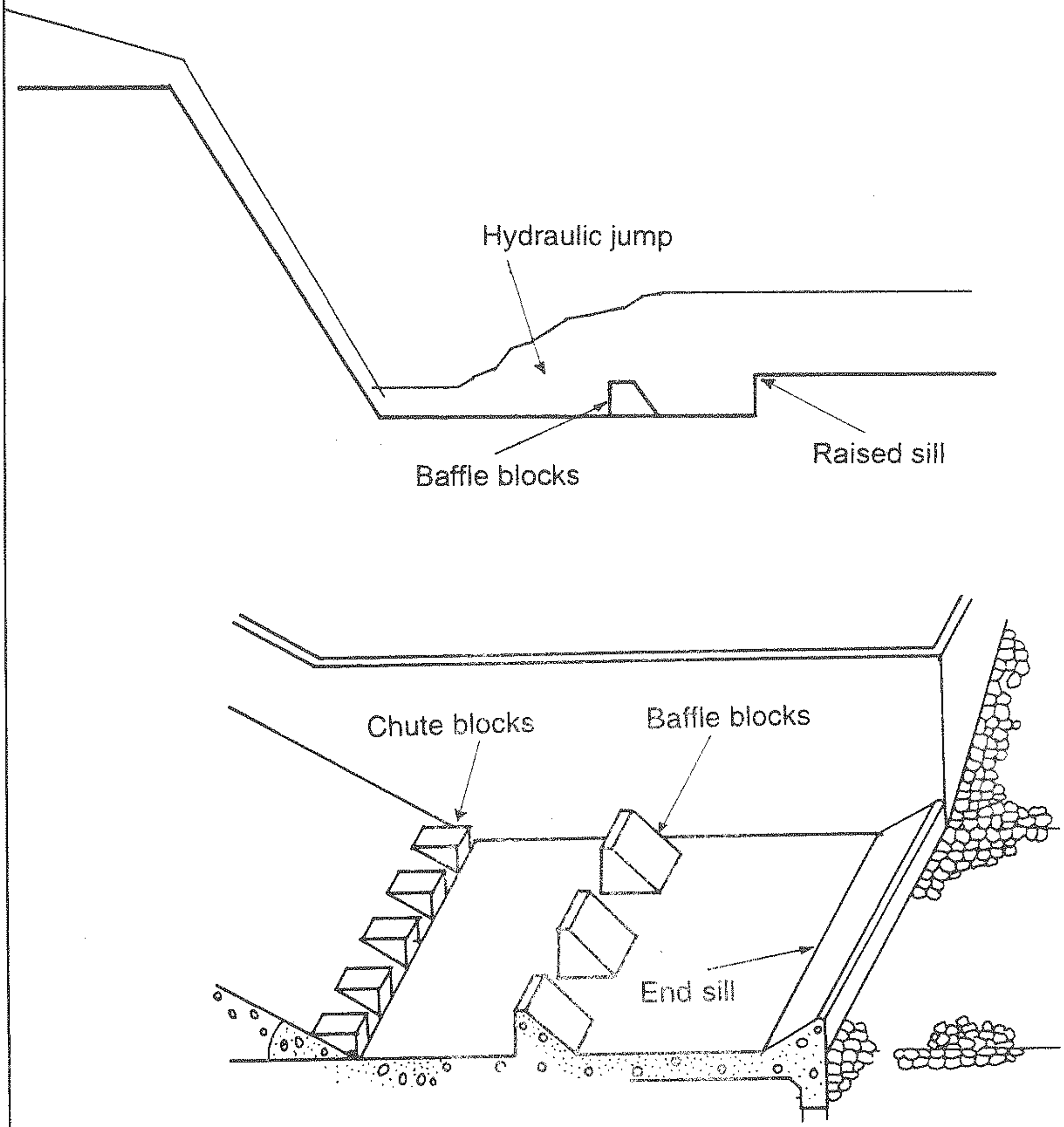
(vii) Plunge Pool ✗

(viii) Stilling Well ✗

(ix) Baffled Spillway ✗

(x) Bucket Dissipator ✗

Figure 5.5
Simple and Appropriate Energy Dissipators for Use in Small Drop Structures in Remote Hill Areas



Efficient Energy Dissipation in a Cascade Drop Structure

Photograph 5C
A Cascade Drop Built in Strong Masonry

Cascade drop structures are very effective in dissipating energy because energy is lost at every step of the cascade.

They also have the advantage of allowing small gradual changes in the direction of flow, as seen above.

The stilling basin at the bottom step of the cascade must be designed as a straight drop with a drop equal to about twice the drop height of the other steps.

WARNING

All Energy must be Dissipated within the Structure

Photograph 5D
A Stilling Basin with Insufficient Water Cushioning

Note the wide stilling basin for energy dissipation.

There is still some turbulence in the downstream canal, probably because of insufficient water cushioning in the basin to still the flow.

Erosion caused by turbulence could have been prevented by stone pitching a short length of the downstream canal.

It is still not too late to provide pitching.

The Use of Small Drop Structures to Check Erosion

Earthen canals with steep gradients can erode due to high flow velocity in the canal.

Bed and bank erosion in such canals can be controlled by either:

- lining canals - an expensive solution when long stretches need to be lined.
- reducing the canal gradient to more gentle slopes - a cheaper alternative.

By providing a series of small vertical drop structures at different locations along the canal a steep canal gradient can be reduced to a more gentle slope.

The number of drop structures needed will depend on:

- the required correction to the canal gradient,
- the drop height of each structure - when several structures are needed drop height may need to be standardised for ease of construction.

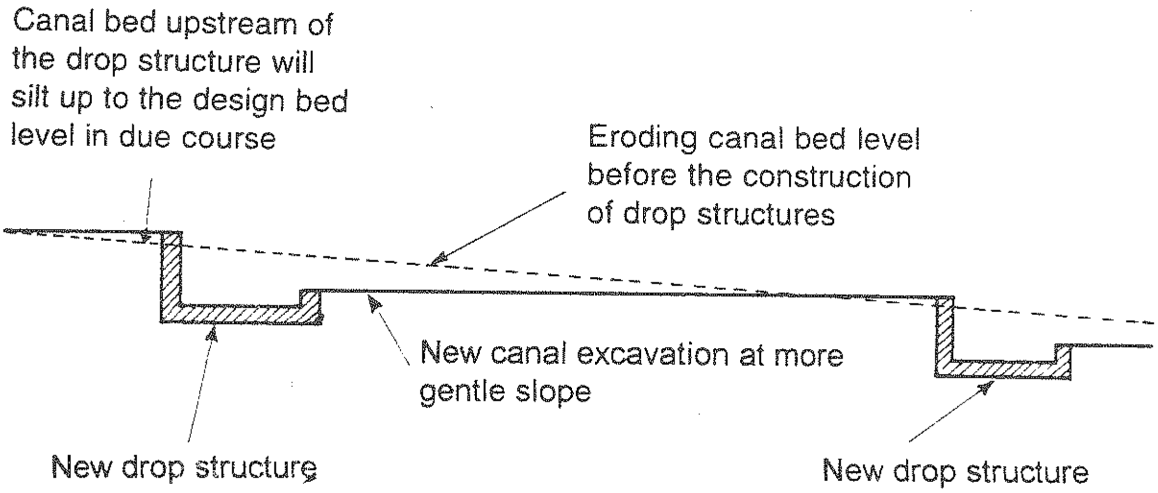
To achieve the objective (reduction in canal gradient):

- the foundation and stilling basin must be cut into solid ground,
- the "crest" on the upstream end of the structure must be built slightly above the existing canal bed, see Figure 5.6.

Figure 5.6
Use of Drop Structures in Rehabilitation Design to Check Canal Erosion

Problem: Danger of canal bed eroding further due to steep gradient.

Solution: Provide small vertical drops at sufficient intervals with crest level set just above the present bed level.



Other, more expensive, but possible solutions are:

- lining the canal with stone/slate,
- lining the canal with masonry,
- lining the canal with concrete.

The Use of Small Drop Structures to Control Water Level

For branch, field or farm outlets to function effectively the water level upstream of the outlet must be maintained at design level.

In canals carrying small flows farmers can effectively control the water level in the parent canal to allow the offtake to draw adequate water from the parent canal. In larger canals, farmer control of water level is often difficult.

Control of the water level in larger canals can be achieved by the use of small drop structures - also called check structures.

In hill canals - because of the relatively steep gradient - every offtake may need a check structure to maintain the water level in the parent canal, see Photograph 5E.

When several check structures are needed standardised drop heights simplify construction.

As for all drop structures, the foundation and stilling basin of check structures must be cut into solid ground, and the "crest" on the upstream end of the structure must be built slightly above the existing canal bed, see Figure 5.7.

Check Structures

Photograph 5E
Series of Small Vertical Drops to Control Water Level in the Canal for Efficient Water Distribution

The above photograph shows two of a series of vertical drop structures built in a branch canal to check water levels and to control canal bed erosion.

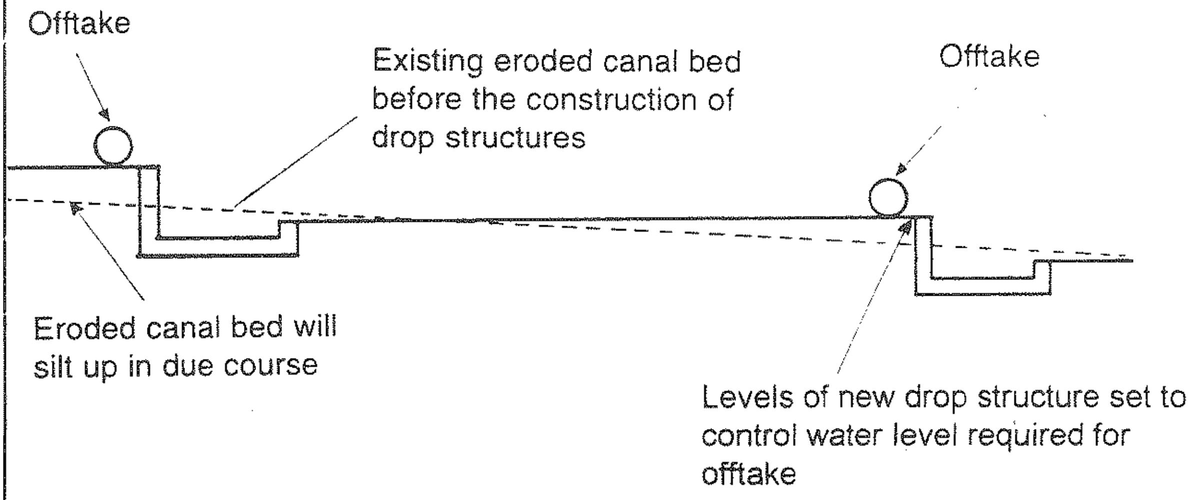
Because they check water levels in the canal they are also called check structures.

Apart from the small amount of undermining behind the wall, which can be remedied, the check structures are all performing well.

Figure 5.7
Use of Drop Structures in Rehabilitation Design to Control the Water Level in the Canal

Problem: Canal bed has eroded and the outlets can no longer draw water from the canal.

Solution: Provide small vertical drops near existing offtake locations, with intermediate drops between offtakes if required, to achieve a more gentle canal slope.



Note: In canals with steep gradients, the water depth may be small requiring control gates in the drop structure for regulating water levels.

Hydraulic Design Calculations for Vertical Drop Structures

Chapter 12.3, "Straight Drop Fall Structures", of Part D2, Vol.2 of the PDSP Design Manuals describes design procedures for vertical drop structures.

The sub-section titled “notes on design” is particularly useful.

The design method, like most hydraulic calculations, is of a “trial and error” nature.

The main hydraulic calculation of the:

- length of drop,
- length of jump, and
- sill height,

requires that an assumption be made of the parameter d_2 - the conjugate depth of the hydraulic jump - and compared to the same parameter d_2 as extrapolated from formulae and graphs.

When the assumed value of d_2 and the extrapolated value of d_2 are equal then one can proceed with the remaining calculations. The flow chart of Figure 5.8 shows the steps of the design process. Details are given in Figures 5.9, 5.10, 5.11 and 5.12.

Alternative Designs

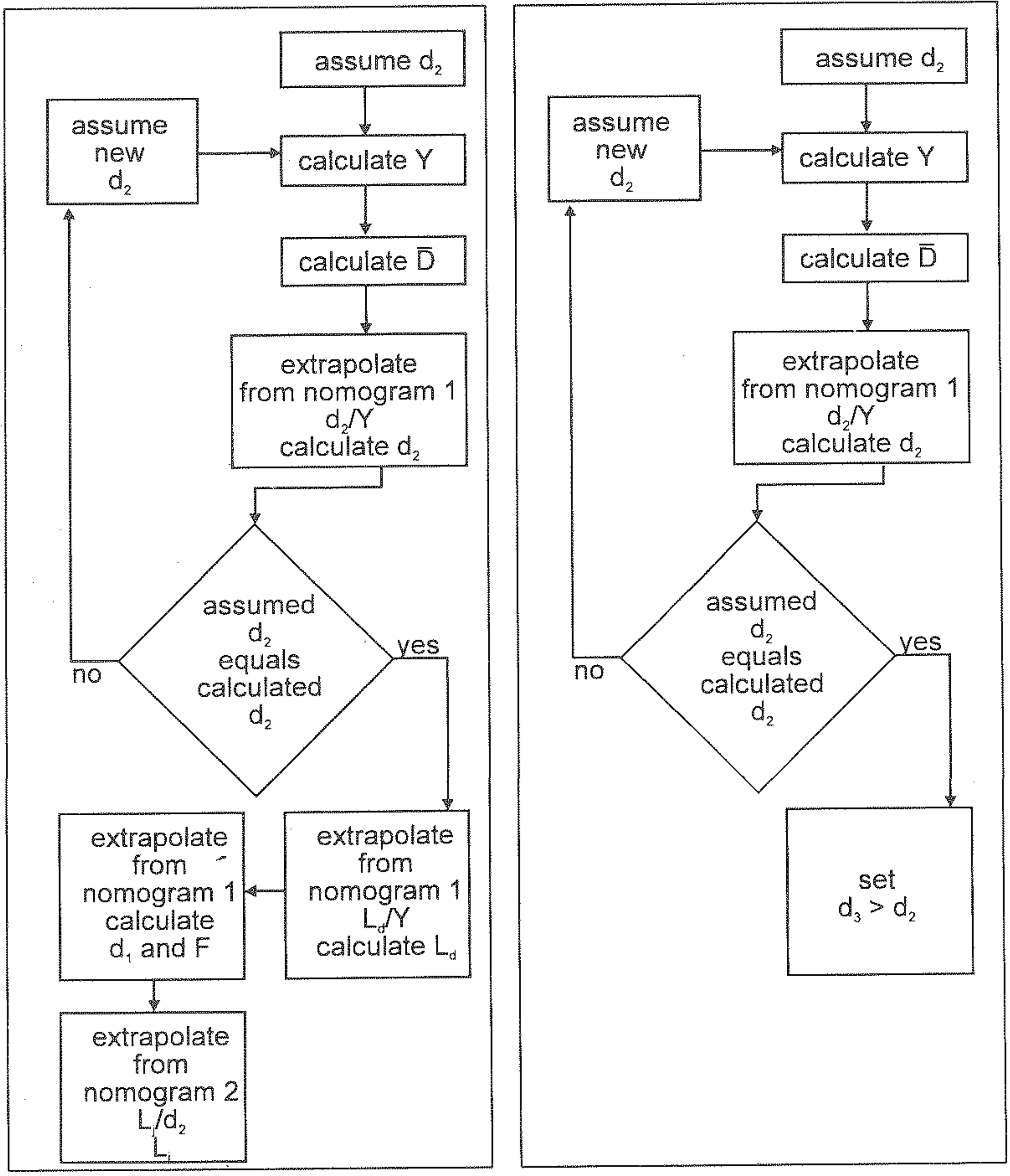
The method described in Chapter 12.3.2 of the PDSP Design Manuals usually results in long, narrow stilling basins.

These are ideal for canals built on mountains with steep cross slopes because it is difficult to build wide structures in such terrain due to lack of building space.

In areas where wider structures are possible, an alternative design with a deep, wide stilling basin may be more appropriate.

Chapter 14.2.3, “Simplified Method for the Design of Drops in Small Canals”, of Part D2, Vol. 2 of the PDSP Design Manuals describes one such design. These designs are recommended only for small drops (below 1 metre) on small canals with a bed width between 0.2 and 1.0 metre and a flow depth between 0.1 and 0.7 metres.

Figure 5.8
Flow Chart for Design Calculation of the Length of Drop (L_d), Length of Jump (L_j) and Sill Height (d_3) of Vertical Drop Structures



Step 1:
For max. Q calculate L_d & L_j using the steps of the flow chart below.

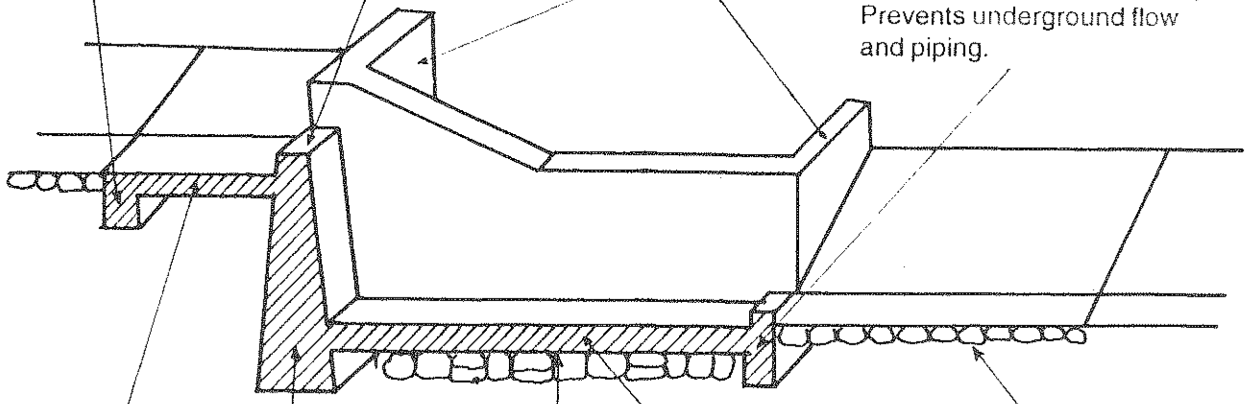
Step 2:
For max. Q / 10 calculate d_3 using steps of flow chart below.

Note: L_d = Length of Drop
L_j = Length of Jump
F = Froude number

Note: $\bar{D}$ is a theoretical parameter called Drop Number and has no relation to any physical dimension of the drop structure.

Figure 5.9

Structural Features of a Typical Vertical Drop Structure and Their Uses



UPSTREAM CUT-OFF (RRM)
Prevents underground flow.
Provides good foundation anchorage.

UPSTREAM RAISED CREST (PCC)
Prevents draw-down and rapid flow.

WING WALL (RRM)
Provides good anchorage of structure into canal sideslopes.

DOWNSTREAM CUT-OFF (RRM)
Prevents underground flow and piping.

DOWNSTREAM PROTECTION (STONES)
Provides erosion protection against turbulence and eddies.

RETAINING WALL (RRM)
Retains earth behind the drop structure.

FLOOR (PCC)
Provides hard wearing surface for hydraulic jump.
Resists impact forces.
Resists abrasive action.

SUB-BASE FLOOR (RRM)
Provides safety against uplift forces.
Provides additional strength to the pcc floor.

UPSTREAM FLOOR (RRM)
Provides hard wearing surface.
Prevents canal bed/side erosion.

Figure 5.10
Vertical Drop Structure:
Important Features to be Designed

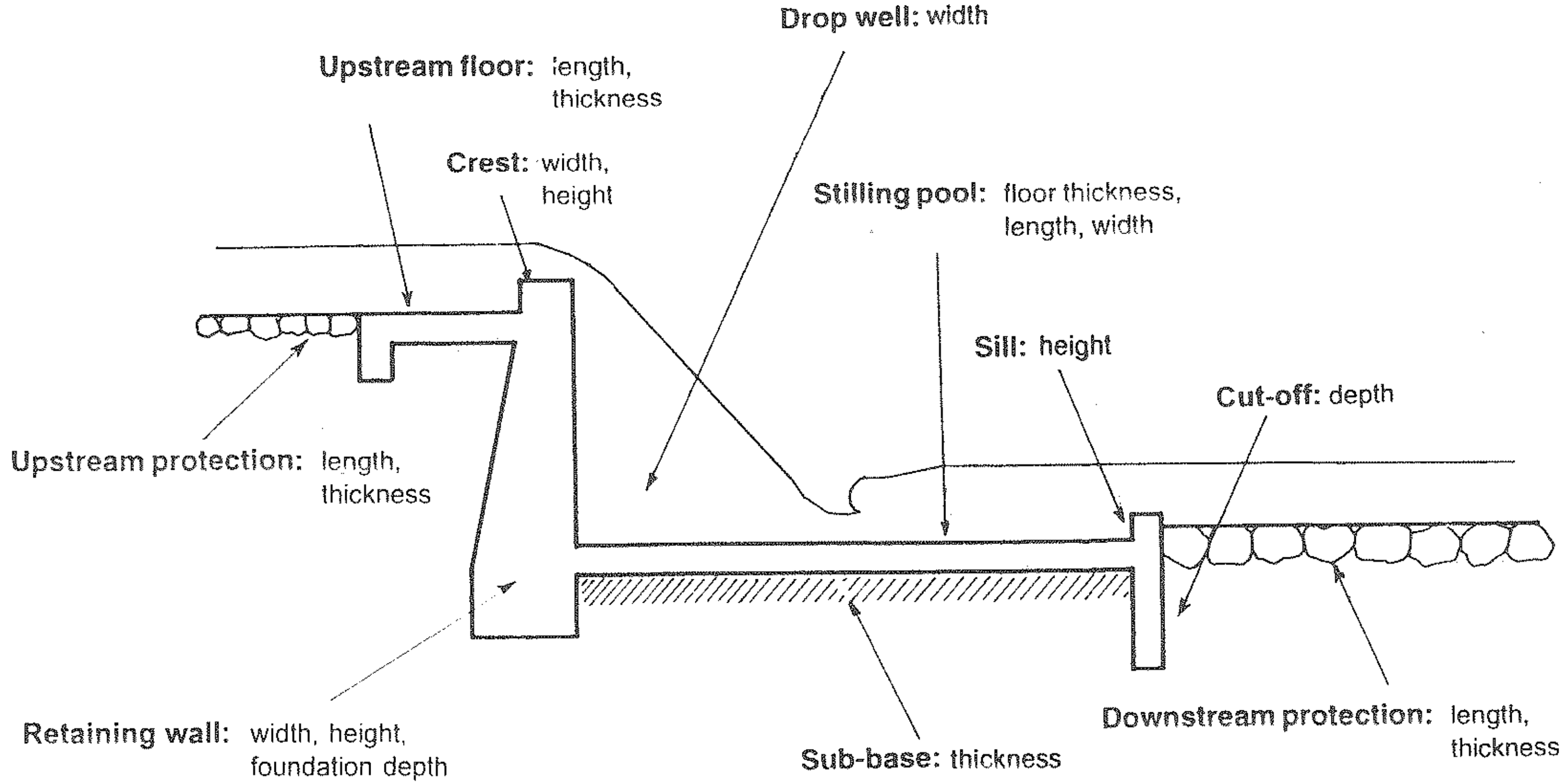
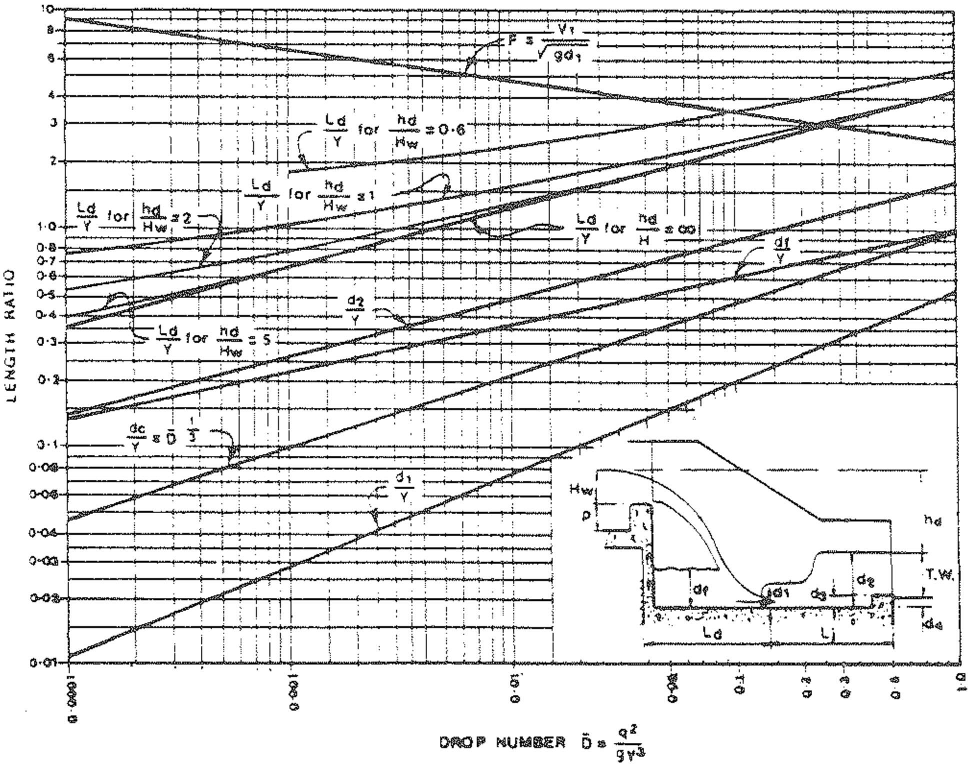
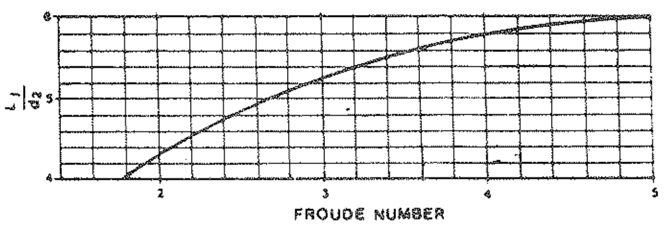


Figure 5.11
Nomograms for the Design of Vertical Drop Structures

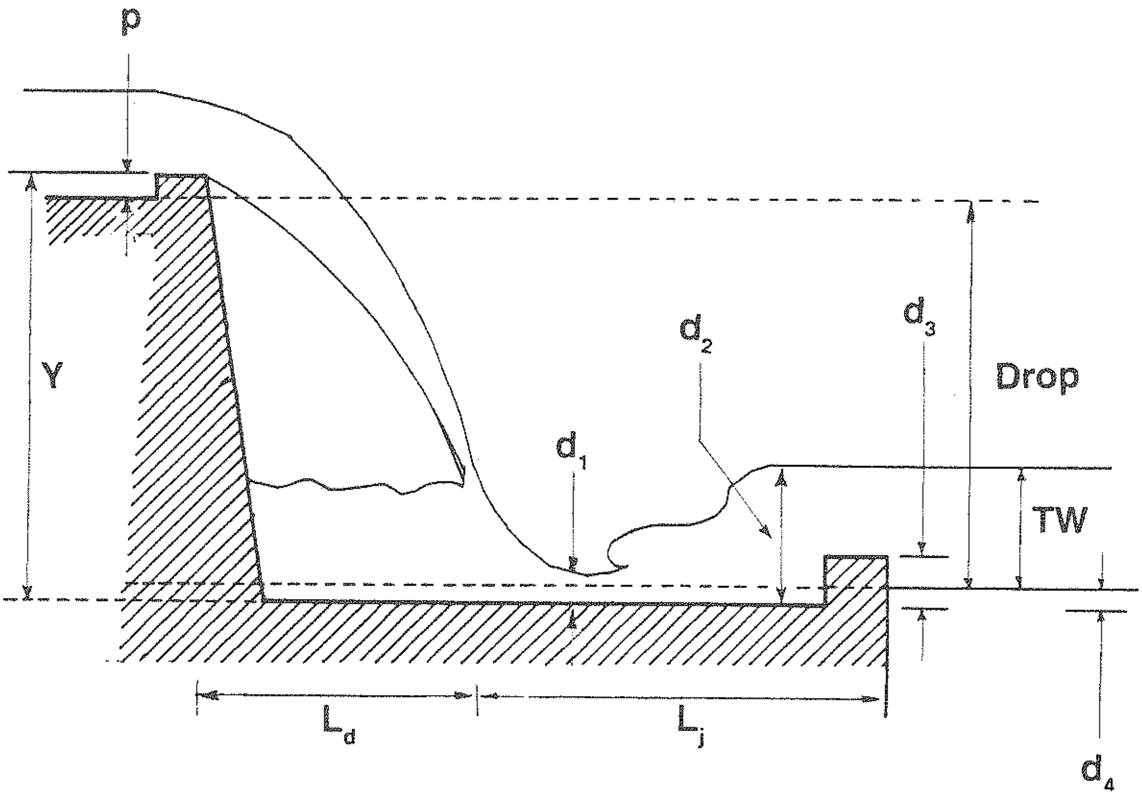


Nomogram 1 for determining the length of drop and height of downstream sill



Nomogram 2 for determining the length of jump

Figure 5.12
Definition Sketch of Physical and Theoretical Parameters Used in the Hydraulic Design of Vertical Drop Structures



$$Y = (d_2 - TW) + \text{Drop} + p$$

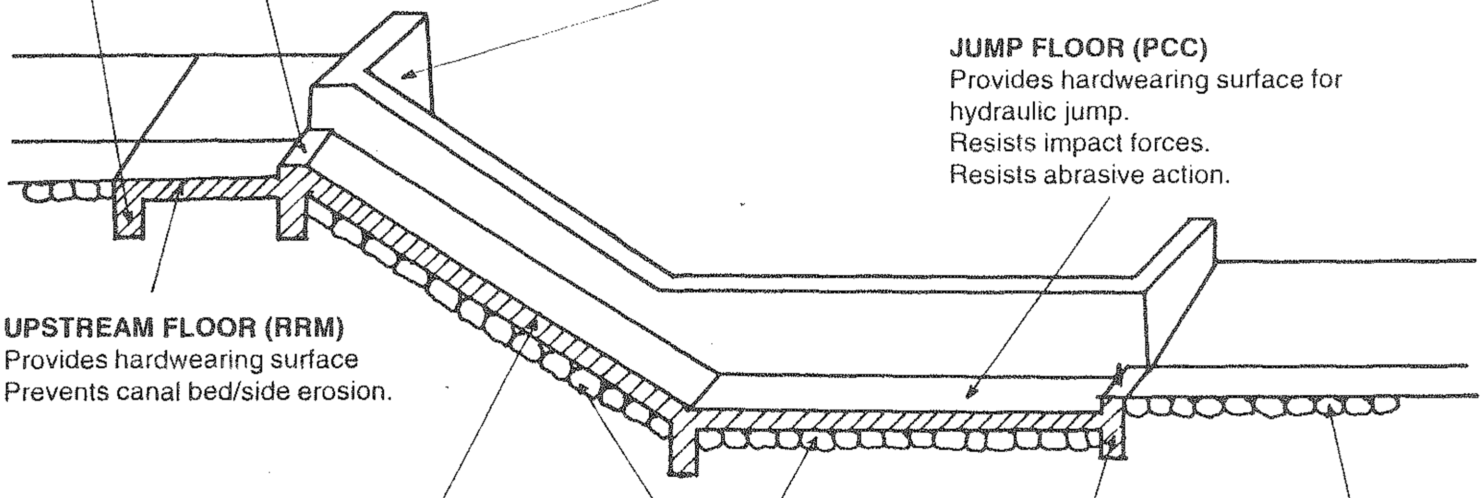
$$\text{Drop Number, } \bar{D} = \frac{q^2}{gy^3}$$

$$\text{Froude Number} = \frac{q / d_1}{\sqrt{gd_1}}$$

(Refer to Chapter 12.3.2 of Part D2, Vol. 2 of the PDSP Design Manuals for more details.)

Figure 5.13

Structural Features of a Typical Chute Drop Structure and Their Uses



UPSTREAM CUT-OFF (RRM)
Prevents underground flow .
Provides good foundation anchorage.

UPSTREAM RAISED CREST (PCC)
Prevents draw-down and rapid flow.

WING WALL (RRM)
Provides good anchorage of
structure into canal sideslopes.

JUMP FLOOR (PCC)
Provides hardwearing surface for
hydraulic jump.
Resists impact forces.
Resists abrasive action.

UPSTREAM FLOOR (RRM)
Provides hardwearing surface
Prevents canal bed/side erosion.

SLOPING FLOOR (PCC)
Provides hardwearing surface against
erosion due to rapid flow.
(negative pressures set up below rapidly
flowing water induce rapid erosion)

SUB-BASE FLOOR (RRM)
Provides safety against
uplift forces.
Provides additional strength
to the pcc floor.

DOWNSTREAM CUT-OFF (RRM)
Prevents underground flow
and piping.

DOWNSTREAM PROTECTION (STONES)
Provides erosion protection
against turbulence and eddies.

Hydraulic Design Calculations for Chute Drop Structures

(Figures 5.13, 5.14, 5.15 and 5.16)

Figure 5.14
Chute Drop Structure:
Important Features to be Designed

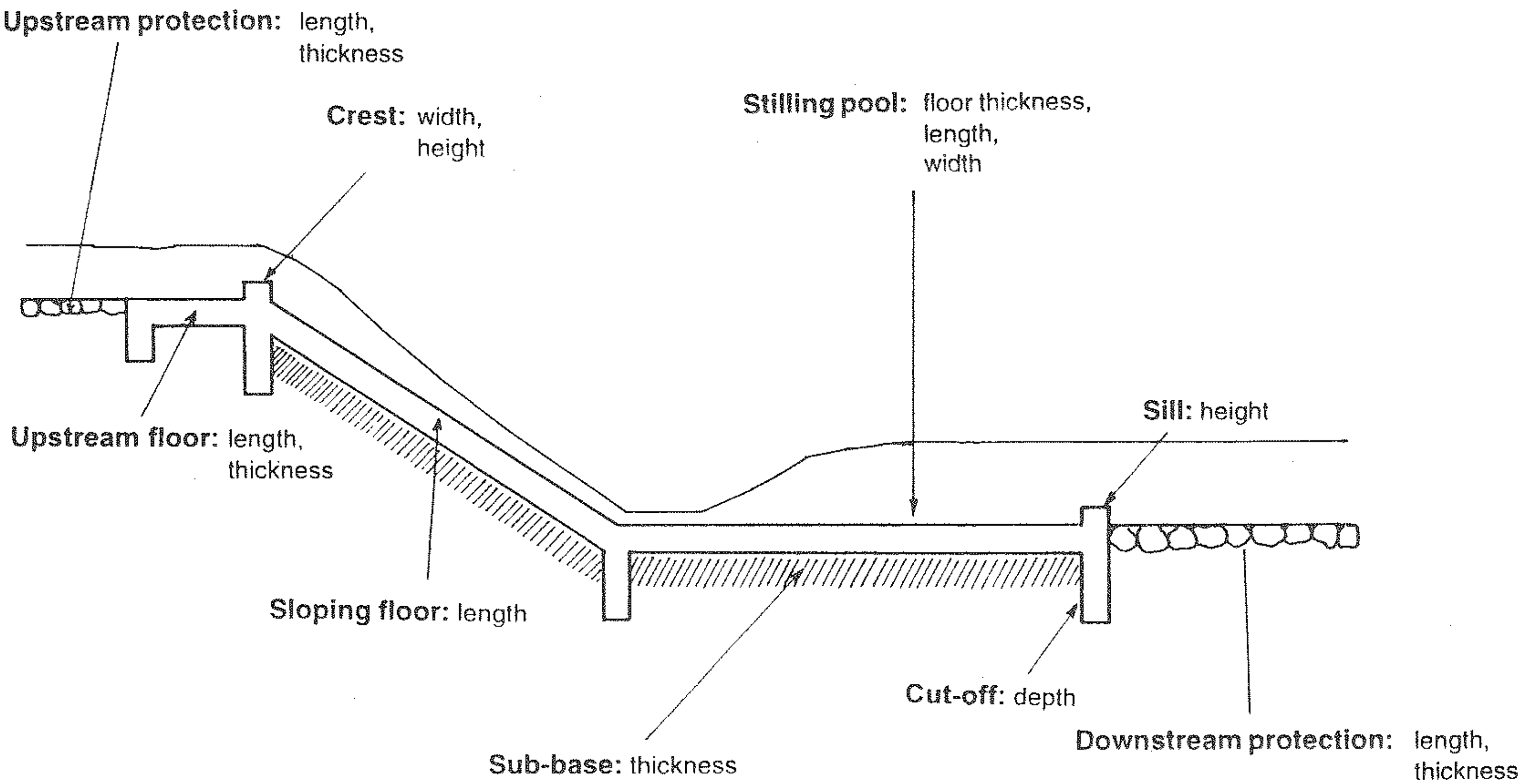
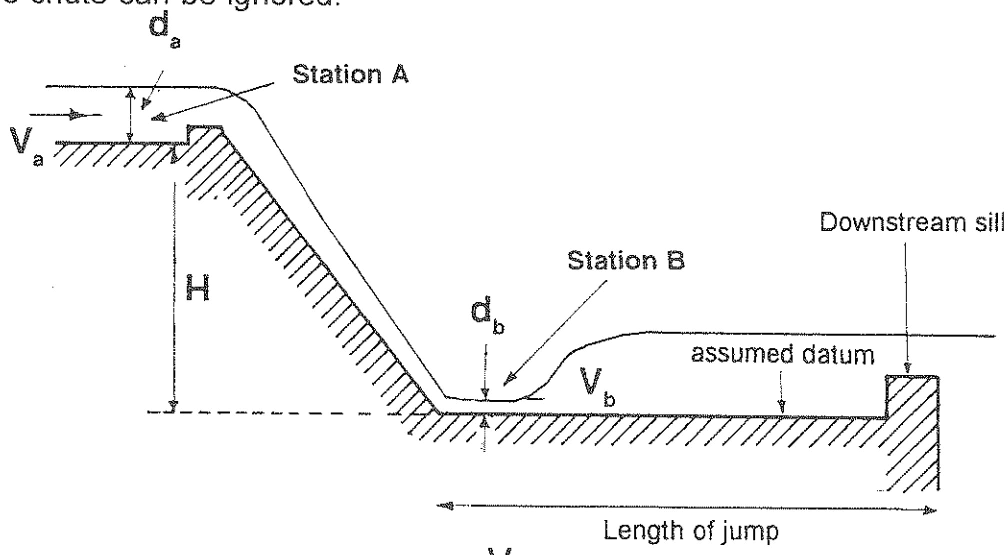


Figure 5.15
Simplified Hydraulic Calculations for Jump Length in Chute Drop Structures

This method is a simplified version of the method outlined in paragraph 14.4 of PDSP, D2, Vol. 2. When the chute is short and steeper than 1:10 the friction loss in the chute can be ignored.



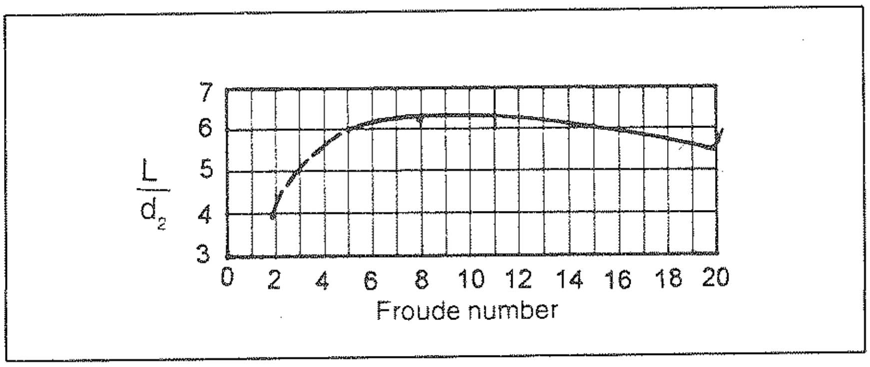
$$\text{Froude Number, } F = \frac{V}{\sqrt{gd}} \quad \text{........ Formula 1}$$

$$\frac{d_2}{d_1} = \frac{1}{2}\left(\sqrt{1+8F^2} - 1\right) \quad \text{...... Formula 2}$$

Method of Calculation

1. Assume total energy (velocity + flow depth + datum) at station A is converted to velocity head at station B.
2. Compute velocity of flow V_b and flow depth d_b at station B.
3. Compute Froude Number at station B using formula 1.
4. Use nomogram 3 to determine L / d_2.
5. Use formula 2, to compute d_2 / d_1.
6. Assuming $d_1 = d_b$, compute d_2 and L the length of jump.
7. Set downstream sill equal to d_2 minus canal flow depth.

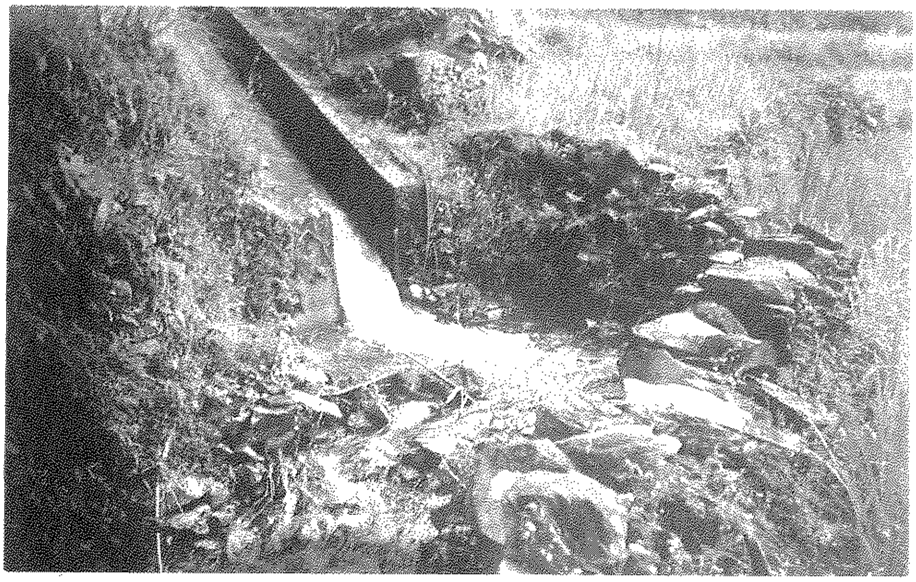
Figure 5.16
Nomogram for the Design of Chute Drop Structures



Nomogram 3 for determining the length of jump

WARNING

Inadequate Stilling Basins can Undermine Safety of Drop Structures



Photograph 5F
A Chute Drop Structure with an Inadequate Stilling Basin

Two major defects can be seen in the design and construction of the stilling basin of the chute drop structure above.

- The basin is short.
- There is a sharp change in the direction of the flow of water in the basin.

Stilling basins, particularly those of vertical and chute drop structures, must be aligned along the direction of incoming flow for maximum effectiveness. A gradual change in the direction of flow in the chute portion of a chute drop may be allowed as shown in Photograph 5C.

In chute drops, unlike cascade drops, all of the water's excess energy must be dissipated at the foot of the drop structure. Chute drops therefore require larger stilling basins.

Hydraulic Design Calculations for Cascade Drop Structures

(Figures 5.17 and 5.18)

Figure 5.17
Cascade Drop Structure:
Important Features to be Designed

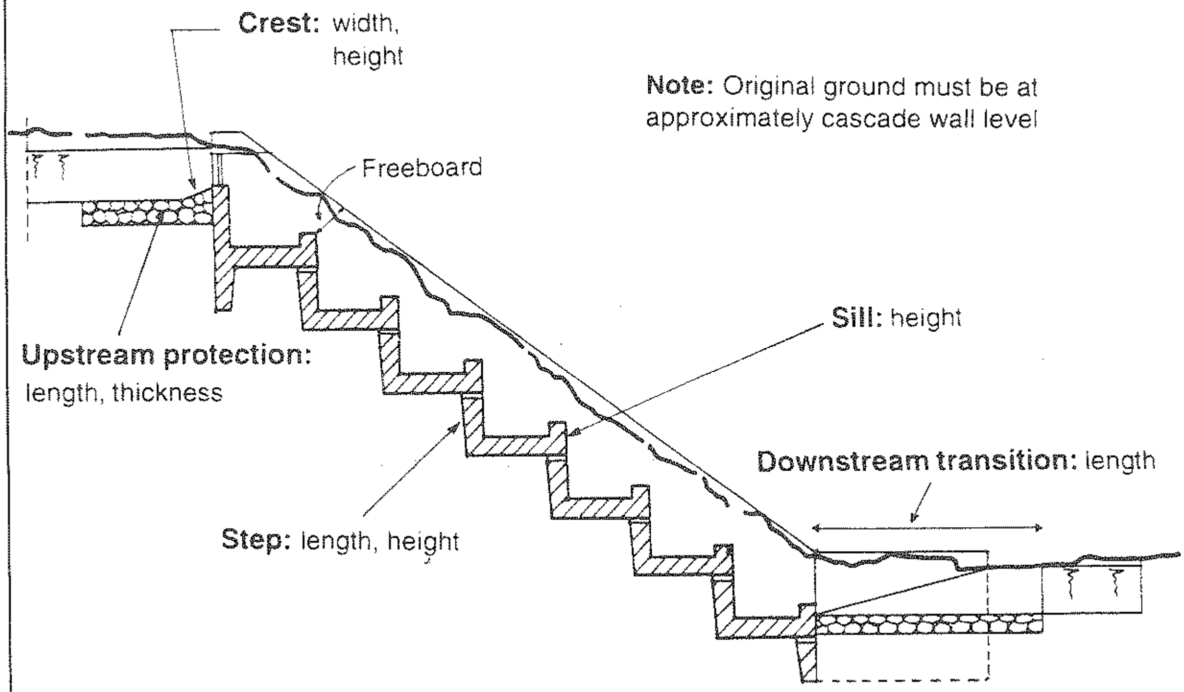
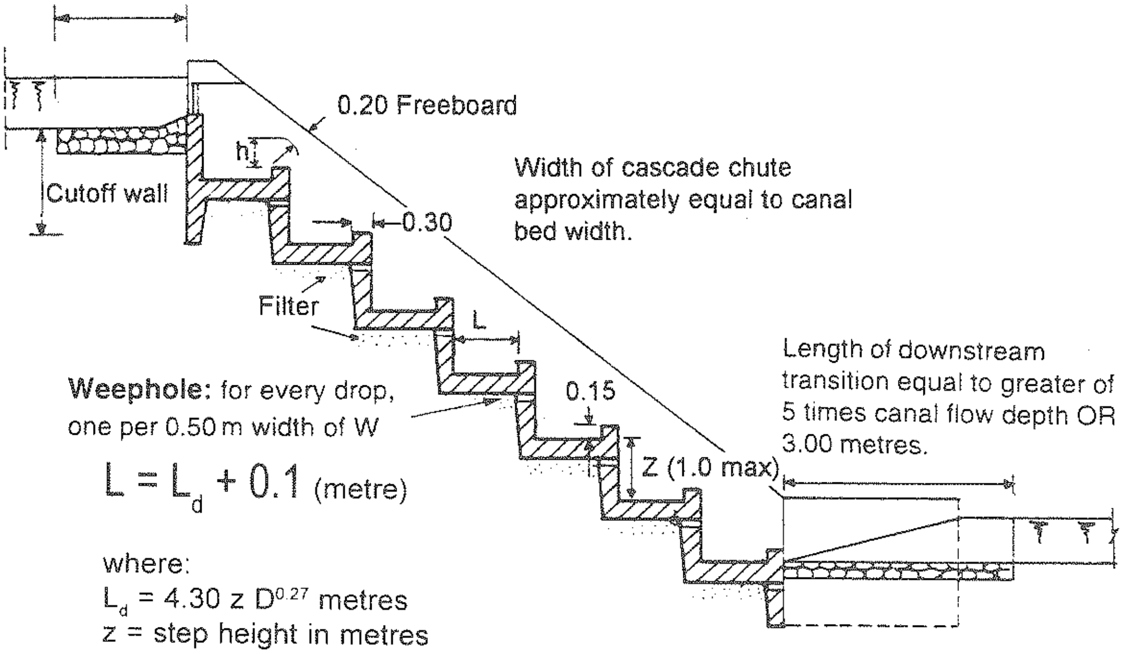


Figure 5.18
Cascade Drop Structure: Design Formulae and Design Data

Length of floor equal to greater of 3 times canal flow depth OR 2.00 metres.



Width of cascade chute approximately equal to canal bed width.

Length of downstream transition equal to greater of 5 times canal flow depth OR 3.00 metres.

Weephole: for every drop, one per 0.50 m width of W

$$L = L_d + 0.1 \text{ (metre)}$$

where:

$L_d = 4.30\, z\, D^{0.27}$ metres

z = step height in metres

$$D = \frac{q^2}{g\, z}$$

where

q = unit discharge (cumec/metre)

g = 9.8

Note: L_d is dependent on D, which in turn is dependent on q, the unit discharge per width of the cascade chute.

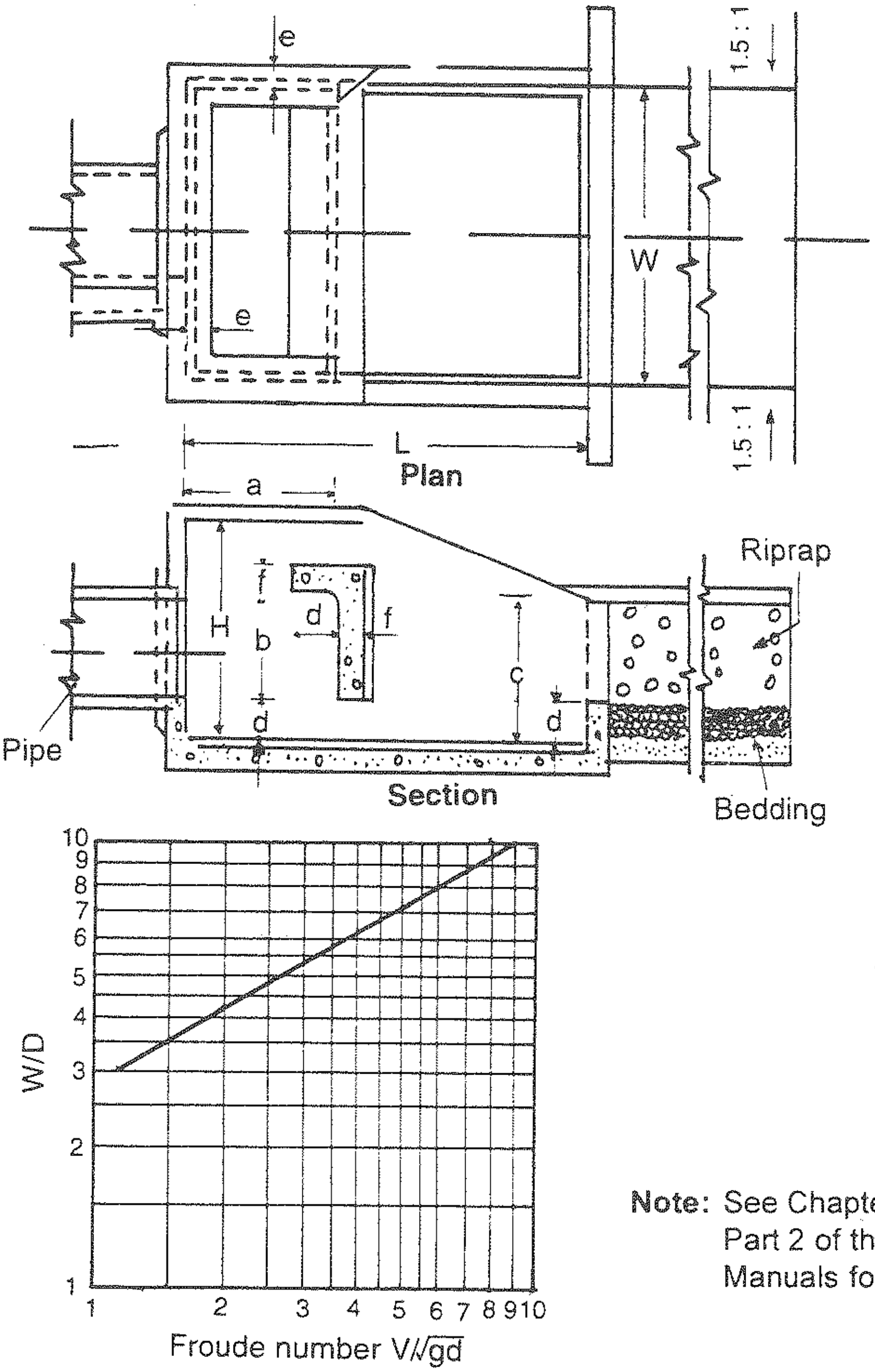
By varying the width within reasonable limits, and by varying the height (Z) of each step, it is possible to arrive at a suitable combination of step height and step length such that the overall slope of the cascade chute matches that of the original ground slope.

Refer to Chapters 12.3.4 of D2, Vol.2 and 3.2.2 of M8, Part 2 of the PDSP Design Manuals for more details.

Hydraulic Design Calculations for Pipe Drop Structures

Figure 5.19

Design Parameters of Baffle Type Basin for Pipe Drop Structures



H = 3/4 W

L = 4/3 W

a = 1/2 W

b = 3/8 W

c = 1/2 W

d = 1/6 W

E = 1/12 W

f = 1/12 W

e_{min} = 15 cm

f_{min} = 15 cm

Note: See Chapter 4.8 of M8, Part 2 of the PDSP Design Manuals for more details.

W = the inside width of the basin

D = the depth of flow entering the basin and is the square root of the flow area

V = the velocity of the incoming flow

Causes of Erosion in Drop Structures

The walls and floors of drop structures can erode due to:

- high flow velocity,
- abrasion caused by suspended gravel or sand.

Erosion Due to High Flow Velocity

Air pockets associated with high flow velocities can cause cavity erosion.

Cavity erosion begins at certain locations in the structure and spreads to neighbouring areas with time.

The following areas in drop structures are particularly vulnerable to cavity erosion (see Figure 5.20):

- raised sills,
- lowered sills,
- sharp changes in curvature,
- sharp changes in slope,
- grooves on the floor,
- rough surfaces, and
- protruding construction joints.

It is difficult to completely avoid cavity erosion in drop structures, but it is possible to reduce its effect by:

- using strong masonry, plaster and concrete,
- ensuring a smooth finish on any surface which will be in contact with water,
- regular maintenance.

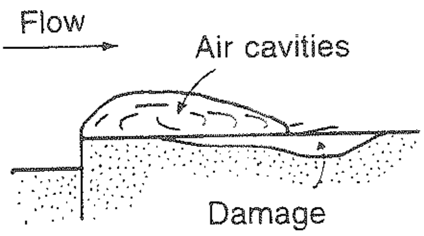
Erosion Due to Abrasion

Abrasion erosion in hydraulic structures is caused by:

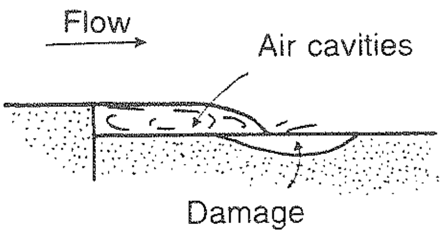
- suspended silt and sand,
- trapped silt, sand and gravel that are in circulation inside enclosed structures such as stilling pools, etc.

It is difficult to completely avoid abrasion erosion in drop structures, but it is possible to reduce its effect by preventing stones and gravel debris falling into stilling pools.

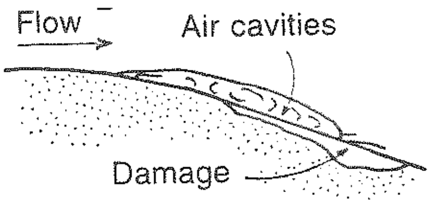
Figure 5.20
What Induces Cavitation Erosion in Hydraulic Structures ?



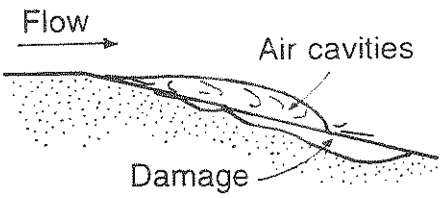
A Raised Sill



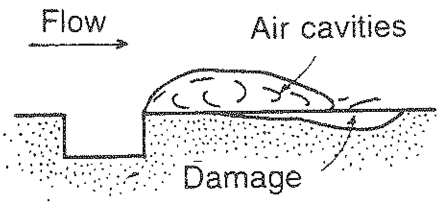
An Abrupt Depression in the Floor



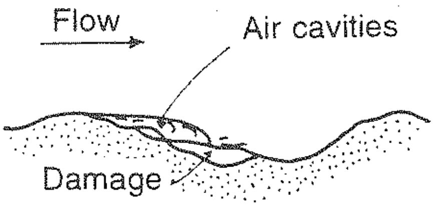
An Abrupt Change in Curvature



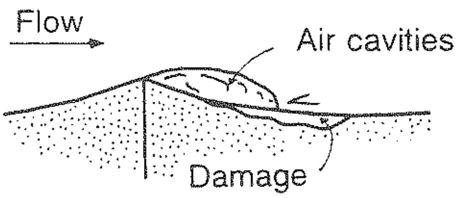
An Abrupt Change in Slope



Transverse Grooves in the Floor



Rough Surfaces



Protruding Joints in Structures

WARNING

Strong Eddies and Turbulence Near Drop Structures can Undermine their Safety

Photograph 5G
A Vertical Drop Structure with Inadequate Stilling Basin and Downstream Protection

Strong eddy currents and turbulence are often present together when stilling basins of drop structures are inadequate.

Eddies can undermine structures leading to their eventual failure.

Wing-walls provide good anchorage for the structure into the earthen side slopes as well as preventing erosion caused by eddying.

Absence of wing-walls and downstream protection have contributed to the undermining that has started at the downstream end of this structure.

Gravel backfilling and stone paving need to be done quickly to prevent any further damage.

WARNING

Rapidly Flowing Water can Erode Even Concrete Floors

Photograph 5H
Eroded Concrete Floor of a Chute Drop Structure

When water flows over steep inclined floors such as the floors of chute drop structures, negative pressures are set up below the sheet of flowing water.

Negative pressure contributes to rapid erosion of the floor. The photograph above shows the erosion caused by the effect of negative pressures on chute floors. Good quality concrete is needed to withstand erosion damage in chutes.

WARNING

Gravel Particles Collecting Inside Drop Structures can Erode Masonry Floors and Walls

Photograph 5I
Eroded Concrete Floor and Masonry
Walls of a Vertical Drop Structure

The side walls, the crest and, particularly, the floor of this vertical drop have started to show signs of erosion. The floors of vertical drop structures are subjected to impact and heavy turbulence forces. Gravel particles carried by the canal flow, and accumulating on the floor, can also contribute to rapid wear and tear caused by abrasion. Hence, the masonry work, plastering and PCC in drop structures must be of very good quality and high strength to prevent quick wear and tear.