Training
Aids for
Dam
Safety

MODULE:

EVALUATION OF HYDRAULIC ADEQUACY

TADS

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Safety

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EVALUATION OF HYDRAULIC ADEQUACY

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PREFACE

There are presently more than 80,000 dams in use across the United States. Like any engineering works, these dams require continual care and maintenance, first to ensure that they remain operational and capable of performing all intended purposes, and then to preclude endangering people and property downstream.

The safety of all dams in the United States is of considerable national, state, and local concern. Given that, the principal purpose of the TADS (Training Aids for Dam Safety) program is to enhance dam safety on a national scale. Federal agencies have responsibility for the safe operation, maintenance, and regulation of dams under their ownership or jurisdiction. The states, other public jurisdictions, and private owners have responsibility for the safety of non-Federal dams. The safety and proper custodial care of dams can be achieved only through an awareness and acceptance of owner and operator responsibility, and through the availability of competent, well-trained engineers, geologists, technicians, and operators. Such awareness and expertise are best attained and maintained through effective training in dam safety technology.

Accordingly, an ad hoc Interagency Steering Committee was established to address ways to overcome the paucity of good dam safety training materials. The committee proposed a program of self-instructional study embodying video and printed materials and having the advantages of wide availability/marketability, low per-study cost, limited or no professional trainer involvement, and a common approach to dam safety practices.

The 14 Federal agencies represented on the National Interagency Committee on Dam Safety fully endorsed the proposed TADS program and have underwritten the cost of development. They have also made available technical specialists in a variety of disciplines to help in preparing the instructional materials. The states, through the Association of State Dam Safety Officials, also resolved to support TADS development by providing technical expertise.

The dam safety instruction provided by TADS is applicable to dams of all sizes and types, and is useful to all agencies and dam owners. The guidance in dam safety practice provided by TADS is generally applicable to all situations. However, it is recognized that the degree to which the methods and principles are adopted will rest with the individual agency, day owner, or user. The sponsoring agencies of TADS assume no responsibility for the manner in which these instructional materials are used or interpreted, or the results derived therefrom.

ACKNOWLEDGMENTS

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Association of State Dam Safety Officials
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MODULE INTRODUCTION

MODULE INTRODUCTION

OVERVIEW OF THIS MODULE

In this module, you will learn basic information about which features of dams are affected by hydraulic forces. You will be able to recognize signs of potential deficiencies and to recommend appropriate actions to identify and predict the nature of destructive processes. Finally, you will learn about remedial actions to arrest or repair damage caused by hydraulic forces.

HOW TO USE THIS MODULE

This module is designed to be used in conjunction with other Training Aids for Dam Safety (TADS) modules. The TADS Learner's Guide lists all of the TADS modules and presents a recommended sequence for completing the modules. You may want to review the Learner's Guide before completing this module.

CONTENTS OF THIS MODULE

This module is divided into five units, followed by three appendixes:

- **Unit I. Overview:** Presents information on types of hydraulic structures, historical experience with accidents and failures caused by hydraulic forces, and the nature of hydraulic structure failures.

- **Unit II. Review And Evaluation Of Project Data:** Provides information on the types of project data that should be studied, information to be obtained, and procedures for comparing as-built design and construction to modern practice and regulatory requirements.

- **Unit III. Investigation And Data Collection:** Discusses procedures for conducting an investigation, including identification of areas for special emphasis, planning and conducting a field investigation, and completing appropriate studies and laboratory analyses.

- **Unit IV. Analysis Of Hydraulic Conditions:** Provides an overview of methods used to analyze deficiencies pertaining to hydraulic structures at dams.

- **Unit V. Remedial Action:** Describes emergency and short-term actions and long-term remedial measures that may be used to deal with identified deficiencies related to hydraulic structures at dams.

CONTENTS OF THIS MODULE (Continued)

- **Appendix A. Glossary:** Defines a number of technical terms used in the module.
- **Appendix B. References:** Lists recommended references that can be used to supplement this module.
- **Appendix C. Research Facilities And Sources Of Assistance:** Lists agencies and laboratories that perform analytical hydraulic studies, and sources for published hydraulic research.

DESIGN OF THIS MODULE

This module consists solely of text instruction. There is no accompanying video presentation.

UNIT I

OVERVIEW

EVALUATION OF HYDRAULIC ADEQUACY

I. OVERVIEW: INTRODUCTION

OVERVIEW

Unit I will introduce you to:

- Fundamentals of hydraulics
- Hydraulic structures at dams
- Historical failures and accidents related to hydraulics
- Types of hydraulic structure problems
  - Structural movement
  - Erosion of earthen slopes
  - Concrete deficiencies
  - Metal degradation
  - Hydraulic flow problems

FUNDAMENTALS OF HYDRAULICS

To evaluate the effect of hydraulic forces on dam safety, you need to know the nature of hydraulics and of hydraulic structures at dams.

What Is Hydraulics?

Hydraulics is the branch of engineering related to the behavior of fluids. Of interest at dams are the discharge rate, velocity, pressure, duration, and depth of flowing water, and the performance of structures that control the water.

Hydraulic structures control the flow of water by:

- Conveying flows
- Combining or separating flows
- Regulating the amount of flow
- Dissipating the energy of flowing water

Structures that perform these functions are subject to hydraulic forces.

HYDRAULIC STRUCTURES AT DAMS

The components of spillways and outlet works are the principal hydraulic structures at dams. Nomenclature for these structures varies; therefore, the terms and definitions from the TADS module Inspection Of Spillways And Outlet Works are used to provide a standard reference base. Appendix A of this module defines hydraulic terms. Refer to Inspection Of Spillways And Outlet Works for illustrations and descriptions of hydraulic structures at dams.

I. OVERVIEW: INTRODUCTION

CONSIDERATIONS FOR HYDRAULIC STRUCTURES

The depth and velocity of flowing water varies at different points in a flow path as water moves through a hydraulic structure. Terms to describe flow conditions include:

- **Critical Flow.** A flow condition when the depth and velocity for a given discharge rate result in minimum specific energy (sum of pressure head and velocity head above a given elevation).

- **Subcritical Flow.** A flow condition when flow is deeper than the critical depth and the velocity is slower than the critical velocity. In a subcritical flow at a given discharge, the same amount of water moves past the same reference point during the same time interval as for the critical flow, but greater depth compensates for reduced velocity.

- **Supercritical Flow.** A flow condition when the flow is shallower than critical depth, with velocity greater than critical velocity. In a supercritical flow at a given discharge, the same amount of water moves past the same reference point during the same time as for the critical flow, but the greater velocity compensates for the shallower depth.

A given hydraulic structure needs adequate structural support for the weight of subcritical flows and resistance to increased abrasion erosion and cavitation damage from the high velocities of supercritical flows.

Table I-1 on the following pages presents some basic information about hydraulic considerations related to structures at dams.

CONSIDERATIONS FOR HYDRAULIC STRUCTURES (Continued)

TABLE I-1. CONSIDERATIONS FOR HYDRAULIC STRUCTURES

Structure	Flow Characteristics	Potential Hydraulic Problems
Entrance Channel	Normally low velocities	Erosion (channel scour) Sedimentation
Return Channel	Often high turbulence	Erosion (channel scour) Non-uniform flow across channel width
Intake Structure (outlet works)	High velocity flow	Debris on trashracks obstructing flow
Control Section . Weir	Conversion from subcritical to supercritical velocities	Cavitation Insufficient aeration causing flow instabilities Erosion (especially in unlined spillways)
. Valves . Gates	Very high flow velocities and turbulence due to abrupt change in the configuration of the structure	Cavitation Insufficient aeration Vibrations Water hammer Structural deformation (distress)
. Submerged Orifice - Port . Tube - Culvert - Siphon	Flows under pressure, completely filling the control section. Rate of flow depends on depth of submergence.	Cavitation Insufficient aeration Abrasion erosion Turbulence Vortices (at low covering depths)

CONSIDERATIONS FOR HYDRAULIC STRUCTURES (Continued)

TABLE I-1. CONSIDERATIONS FOR HYDRAULIC STRUCTURES
(Continued)

Structure	Flow Characteristics	Potential Hydraulic Problems
Water Conveyance		
. Conduit (pipe, sluice, penstock) . Tunnel	Generally pressurized flow when unregulated or free water surface when regulated at entrance. Wide range of high flow velocities.	Insufficient aeration Cavitation Water hammer Leakage Abrasion erosion
. Discharge Channel (chute)	Free water surface, wide range of flow velocities, usually increasing.	Insufficient aeration Cavitation Abrasion erosion Standing waves resulting in non-uniform flow Uplift pressures
Energy Dissipator		
. Baffles . Stilling Basin . Flip Bucket . Impact Basin . Stilling Well . Plunge Pool	High flow velocities, high turbulence; exposure to great hydraulic forces.	Cavitation Abrasion erosion (ball-milling) Erosion Vibrations Displacement Sweepout (loss of tailwater necessary to maintain jump in basin caused by erosion in the return channel) Excessive tailwater Undercutting Uplift pressures Overturning Headcutting

I. OVERVIEW: SIGNIFICANCE OF HYDRAULIC CONDITIONS

INTRODUCTION

The hydraulic conditions at a dam are of major importance to the safety of the dam. The water stored behind a dam represents potential energy and the impounded water exerts static hydraulic forces on the dam. The evaluation of static hydraulic forces relevant to structural stability is addressed in the following TADS modules:

- Evaluation Of Seepage Conditions
- Evaluation Of Concrete Dam Stability
- Evaluation Of Embankment Dam Stability And Deformation

When ultimately released, impounded water subjects the hydraulic structures of a dam and the downstream channel to significant forces. This module is principally concerned with those dynamic hydraulic forces (those of water in motion). The safety of the dam depends on the ability of the hydraulic structures to perform satisfactorily over a wide range of flow conditions.

Hydraulic structures with inadequate discharge capacity or strength to resist the imposed hydraulic forces are subject to damage or failure. Failure of a hydraulic structure can, in turn, increase the discharge, result in a loss of control, and in some cases lead to failure of the dam and possible catastrophic flooding.

I. OVERVIEW: HISTORICAL PERSPECTIVE

SUMMARY OF LESSONS FROM HISTORY

A study of past dam failures and incidents attributed to hydraulic factors reveals the importance of recognizing conditions that could potentially lead to damage or failure of the structure or dam.

Table I-2 lists causes and the corresponding numbers of all recorded dam incidents (failures and accidents) occurring in the United States through 1979. Bold print highlights the categories most closely related to hydraulic factors.

TABLE I-2. CAUSES OF DAM INCIDENTS

Incident Causes	Number Of Incidents	Embankment Dam Incidents	Concrete Dam Incidents	Other	Percent Of All Incidents
Overtopping	**37**	**25**	**9**	**3**	**13**
Flow erosion	**34**	**31**	**3**		**12**
Slope protection damage	**13**	**13**			**5**
Embankment leaking, piping	37	37			13
Foundation leaking, piping	66	54	11	1	23
Sliding	35	33	2		12
Deformation	37	32	2	3	13
Deterioration	**11**	**5**	**6**		**4**
Earthquake instability	3	3			1
Faulty construction	5	3	2		2
Gate failures	**7**	**4**	**3**		**2**
TOTALS	285	240	38	7	100
Totals For Hydraulically Related Causes	**102**	**78**	**21**	**3**	**36**

SOURCE: Safety of Existing Dams (National Academy Press, 1983), citing Lessons From Dam Incidents (USA, ASCE/USCOLD, 1975), and supplementary survey data supplied by USCOLD.

I. OVERVIEW: HISTORICAL PERSPECTIVE

CASE STUDIES

Table I-3 summarizes a number of case histories of incidents involving hydraulic structures.

TABLE I-3. HYDRAULIC INCIDENTS: CASE HISTORIES

DESCRIPTION	CIRCUMSTANCES	REMEDY
<u>RISERS</u> Salem Fork Watershed, West Virginia: 30-year-old concrete spillway/outlet works risers.	Cracks and spalling caused loss of anchoring for trashracks. Displacement of trashrack would have left risers susceptible to blockage.	Large areas of deteriorated concrete were replaced, smaller cracks patched, and trashracks repaired or replaced.
<u>GATED: OPEN CHANNEL SPILLWAY</u> Dickinson Dam, North Dakota: Crest (bascule or bottom-hinged) type gate with short protrusions above the gate leaf to supply air to the underside of the flow.	The gate was partially opened. Low pressure under the gate resulted in extreme loading that forced the gate open further and caused some parts to fail.	Specially designed air tubes were installed to permit full aeration of the nappe.
<u>TUNNEL SPILLWAY</u> Glen Canyon Dam, Arizona: Two steeply inclined, 41-foot-diameter tunnel spillways with 500 feet of vertical drop. Each spillway was designed to pass 180,000 cubic feet of water per second.	Both spillways operated for over 2 months. One spillway passed up to 32,000 cubic feet of water per second, and the other passed up to 27,000 cubic feet per second. Extensive cavitation and erosion damage occurred at the elbow at the bottom of the inclined portion of each spillway during the passage of the flood.	Model studies were used to determine the size and location of an aeration slot in the inclined portion of the tunnel that would eliminate cavitation. The damaged concrete was repaired and an aeration slot was added to each spillway.

CASE STUDIES (Continued)

TABLE I-3. HYDRAULIC INCIDENTS: CASE HISTORIES (Continued)

DESCRIPTION	CIRCUMSTANCES	REMEDY
CONCRETE DAM Gibson Dam, Montana: Concrete arch dam, 199 feet high.	The dam was overtopped for 20 hours with a maximum depth of 2 feet, 3 inches of water. The abutments were severely eroded.	The abutments were armored with reinforced concrete slabs that were anchored to the abutments with grouted anchor bars. Concrete piers were installed at uniform spacing along the top of the dam to split any future overflows and provide aeration under the nappe. The aeration would allow the flow to spring free of the downstream face, and prevent oscillations of the nappe that could produce vibrations in the dam.
OUTLET WORKS TUNNEL Trinity Dam, California: Jet flow gate releasing into a free flow tunnel; air supplied by a duct installed in the air space along the crown of the tunnel. The gate was operated under a head of more than 350 feet.	Cavitation damaged the concrete lining downstream from the gate liner. Initial action was to cut a rectangular slot into the concrete lining just downstream of the gate liner and weld a bar to the edge of the steel liner to serve as an orifice plate to direct flows over the slot. No further cavitation occurred until a gate leaf failed to fully close, probably because of impact from debris. The orifice plate broke, permitting water to strike the downstream edge of the rectangular slot, deflect upward, and strike the air duct, which washed out of the tunnel. Lack of air resulted in extensive cavitation and erosion damage to the tunnel lining.	Model studies were performed to establish corrective action. The studies determined the configuration of an aeration slot, which was installed at the downstream end of the gate liner. They also determined the sizing of the air duct that was installed in the crown of the tunnel. The model studies also determined that a deflector shield was needed at the downstream end of the tunnel to prevent release back-spray from flooding the air duct inlet.

CASE STUDIES (Continued)

TABLE I-3. HYDRAULIC INCIDENTS: CASE HISTORIES (Continued)

DESCRIPTION	CIRCUMSTANCES	REMEDY
AUXILIARY SPILLWAYS South Fork Watershed, West Virginia: 19 significant and high hazard dams with excavated earthen emergency spillway channels with vegetative cover. Channel slopes varied between 10 and 50 percent.	Severe flooding accompanying a hurricane-related storm resulted in spillway flows in the watershed for a duration of 20 to 40 hours. The depth of the discharges above the control sections of the spillways ranged from 2 to 5 feet. Discharge and return channels eroded, with the most severe erosion downstream from discharge channels.	Eroded material was replaced and vegetative cover reestablished.
SIDE CHANNEL SPILLWAY Big Sandy Dam Spillway, Wyoming: Crest wall under the ogee section constructed with an ineffective drainage system in its foundation.	The crest wall was constructed against a non-freedraining foundation. Anchor bars installed to hold the wall in place against uplift were too short to be effective. Foundation seepage froze, causing the wall to rotate outward from the foundation.	The crest wall was removed, and the foundation was excavated and replaced with a gravel bedding. Perforated drains were installed in the gravel to provide drainage. Longer anchor bars were installed. Rigid insulation was installed between the new concrete crest wall and the gravel bedding. A double-line grout curtain was provided upstream to reduce seepage.
SPILLWAY CHANNEL Dickinson Dam, North Dakota: 15-inch-thick concrete floor slabs without waterstops over clay drain pipes and a gravel filter blanket, supported by a soft sandstone foundation.	Water seeped through floor slab joints, eroded foundation material, and collected in the filter and froze during the winter, lifting some slabs. One slab cracked and rose at the upstream end, with the transverse edge protruding into the flow. Increased uplift pressures during spillway releases floated the slab and several adjoining slabs out of place.	Floor slabs were replaced with redesigned slabs. Drains with filters were reinstalled. Slabs were constructed with control joints containing waterstops to prevent seepage and continuous reinforcement to minimize joint movement and deflection.

CASE STUDIES (Continued)

TABLE I-3. HYDRAULIC INCIDENTS: CASE HISTORIES (Continued)

DESCRIPTION	CIRCUMSTANCES	REMEDY
SPILLWAY CHUTE AND STILLING BASIN Big Sandy Dam, Wyoming: Stilling basin constructed without floor drains. Walls constructed against excavated slopes without provisions for drainage. Chute floor leading to the stilling basin had a drainage system that ended above the standing (nonoperating) pool of the stilling basin.	The stilling basin walls became severely cracked due to frost action. Weepholes were drilled, but were ineffective. Seepage appeared along the undrained portion of the floor of the chute near the standing pool. Weepholes were drilled through the floor to reduce uplift pressures. After several years, sediment was observed to have washed through each floor weephole, indicating possible loss of foundation material through the drains. A minor spillway flow caused hydraulic uplift and failure of the chute floor below the drainage system.	The chute and stilling basin were completely replaced with structures of the latest state-of-the-art designs. A perforated drainage system embedded in gravel bedding was installed under the chute and stilling basin floors. The drains were insulated, except under the standing pool in the basin. Anchor bars were grouted into the foundation to resist uplift pressures. Waterstops were provided in floor joints. Pervious fill was used behind the walls of the chute and stilling basin.
STILLING/HYDRAULIC JUMP BASINS Navajo Dam, New Mexico: Basin receives flow from outlet works hollow jet valves. * * * Oologah Dam, Oklahoma: Basin receives flows from dual 19-foot diameter conduits.	Heavy damage occurred to concrete because of ballmilling by rocks drawn into the basin from the return channel. Excessive wave action also occurred. * * * Twelve years after construction, significant abrasion-erosion damage and ballmilling action occurred with complete loss of one baffle block. Basin surfaces and baffle blocks were rebuilt with high-strength epoxy concrete. After 6 years, additional erosion damage occurred.	Steel lining was installed in the basin. The return channel was lined with concrete. * * * The conclusion that the original concrete was of poor quality was refuted by the subsequent damage to the highly durable epoxy concrete. Basin and concrete surfaces are repaired periodically because of continual deterioration caused by heavy discharges.

I. OVERVIEW: HISTORICAL PERSPECTIVE

CASE STUDIES (Continued)

TABLE I-3. HYDRAULIC INCIDENTS: CASE HISTORIES
(Continued)

DESCRIPTION	CIRCUMSTANCES	REMEDY
IMPACT BASIN Saltlick Creek Watershed, West Virginia: Reinforced concrete, 22 years old.	Poor consolidation of concrete at a construction joint caused a crack to develop completely across headwall and into both sidewalls, extending completely through the wall. Constant leakage through the crack from the principal spillway drainage system caused deterioration of the concrete and the reinforcement.	Damaged concrete was removed and replaced to seal the crack.
PLUNGE POOL AND RETURN CHANNEL Wheeling Creek Watershed, West Virginia: Receive flows from principal spillway conduit; 11 years old.	Rock from the riprap lining of the plunge pool was washed loose and deposited in the return channel. The rock deposits formed a small dam in the return channel, raising the water level in the plunge pool and partially submerging the conduit outlet. With the water level above the pipe invert, water no longer plunged, but skimmed at high velocities across the pool, causing additional erosion and sedimentation. Eventually the water level rose high enough to negate the energy dissipation function of the plunge pool. Finally, a large section of the return channel eroded away.	An impact basin was installed at the conduit outlet and the return channel was rebuilt.

CASE STUDIES (Continued)

TABLE I-3. HYDRAULIC INCIDENTS: CASE HISTORIES (Continued)

DESCRIPTION	CIRCUMSTANCES	REMEDY
<u>RETURN CHANNEL</u> Grapevine Dam, Texas: Spillway with ogee crest, concrete apron, and excavated return channel joining a natural stream; 19 years old.	Heavy rains caused moderate spillway flows. Peak discharge was only about 5 percent of design discharge, and maximum head on the spillway was only about 16 percent of design head. However, flow velocities eroded a trench that averaged 15 feet deep in the upper portion of the natural stream, below the excavated return channel. The erosion progressed upstream into the return channel, in a process known as headcutting. Ability to pass major flood flows without loss of lake storage appeared doubtful.	Physical model tests of the existing spillway and proposed changes were conducted to evaluate erosion potentials during major flood flows. The model findings resulted in construction of a sloped extension to the concrete apron that directed flows to a new concrete stilling basin with baffle blocks set at a lower elevation than the original return channel. A riprap blanket was added downstream from the basin to protect the channel from further major erosion.

I. OVERVIEW: TYPES OF HYDRAULIC STRUCTURE PROBLEMS

INTRODUCTION

Major failures of hydraulic structures have been related to the control and release of water. Flowing water affects all surfaces that are designed to contain it. Some hydraulic failures occur rapidly, within hours. Others take place gradually, over a period of years.

Hydraulic performance can be affected by structural, mechanical, and geotechnical considerations.

Waterborne chemicals can dissolve minerals in both foundation rock and concrete aggregate, and can also corrode metal. Flowing water and wave action can loosen and wash away particles from natural and constructed materials. The abrasive action of sediments and other particles suspended within flowing water hastens surface deterioration.

A number of hydraulic phenomena inherent in flowing water can result in the destruction of conveyance structures. High velocity flows under low pressure conditions can cavitate all types of materials. Also, momentum fluctuation in the flows sets up vibration displacement that causes fatigue failure in materials and structures. These fluctuations can also cause dynamic pressure buildups resulting in surges or water hammer.

The buildup of seepage pressure head within, under, or behind impervious structures tends to uplift or overturn them.

The most significant consequence of hydraulic structure failure would be the failure of the dam itself. Failure of a spillway or other water conveyance structure could also result in the loss of the reservoir and creation of a downstream flood wave similar to that experienced with a breach of the dam. Destruction of a localized portion of a conveyance structure may not result in a sudden loss of the reservoir, but continued neglect eventually could lead to a complete dam failure.

The following types of problems may affect hydraulic structures:

- Structural movement
  - Uplift
  - Wall failure
  - Settlement

- Hydraulic flow problems
  - Inadequate design
  - Cavitation
  - Abrasion erosion
  - Water hammer
  - Vibrations

I. OVERVIEW: TYPES OF HYDRAULIC STRUCTURE PROBLEMS

INTRODUCTION (Continued)

- Erosion
  - Rainfall runoff
  - Discharges

- Concrete deficiencies
  - Cracking
  - Deterioration
  - Leakage

- Metal deficiencies
  - Corrosion
  - Cracking fatigue from vibrations

STRUCTURAL MOVEMENT

Most forms of structural movement can produce undesirable flow conditions, and possible failure of the hydraulic structure. The effects on hydraulic performance of the three following types of structural movement will be discussed:

- Uplift
- Wall failure
- Settlement

Causes of structural movement include:

- Earthquakes
- Inadequate drainage
- Exposure to greater than design load
- Faulty design and/or construction
- Inadequate foundation

For additional information about structural movement, refer to the TADS modules <u>Evaluation of Concrete Dam Stability</u> and <u>Evaluation of Embankment Dam Stability and Deformation</u>.

I. OVERVIEW: TYPES OF HYDRAULIC STRUCTURE PROBLEMS

Uplift

The hydraulic pressure exerted by seepage on the underside of concrete hydraulic structures is frequently great enough to overcome the weight of the structure, causing uplift or failure by overturning or sliding. Susceptible structures include:

- Lined channels
- Spillway aprons
- Entrance channel slabs
- Stilling basins
- Spillway gravity sections

Some submerged or partially submerged structures may be uplifted or floated when dewatered. Care should be taken to determine if structures have been designed to withstand this unbalanced hydraulic loading.

A critical situation exists when a floor panel of a spillway moves vertically and creates obstructions to the flow. This partial obstruction of the flow can cause failure of the downstream floor panel during the passage of high velocity flows. The impact of the water against the upstream edge of the obstructing panel, along with increased pressures under the panel caused by seepage through the uplift joint, could cause rapid removal of the floor. Small movements of the floor also could result in cavitation damage in the downstream reaches of the hydraulic structure.

Differential movement that raises an upstream floor panel higher than the downstream panel often results in minimal or no damage to the structure. The offset can in fact provide aeration under the flow if there is an uninterrupted path to the air. Potential exists for cavitation during high velocity flows if air cannot be drawn in under the flow at the offset.

Wall Failure

Walls are used to contain the flow in a chute, channel, or basin. The failure of a wall in these structures could result in the erosion of adjacent material. Failed wall sections could also partially block the channel and thus reduce discharges. Wall sections without fill behind them could rotate outward during discharges due to the internal hydraulic load. In both cases, the water will flow out at the failed wall sections, resulting in the erosion of adjacent materials and possible undermining of the structure. Wall sections and backfill materials that fall into the channel could progressively knock out downstream wall panels and damage the floor as they are washed downstream.

Not all wall movements indicate impending wall failure. Some movement is anticipated in the walls of all hydraulic structures. Differential movements often take place between walls of different thicknesses, or between cantilevered walls adjacent to counterforted walls. Generally these movements of properly designed walls cause no hydraulic flow problems.

I. OVERVIEW: TYPES OF HYDRAULIC STRUCTURE PROBLEMS

Settlement

Settlement of hydraulic structures is caused by settlement of the underlying material comprising the foundation for the structure. Generally speaking, settlement may be uniform or nonuniform (otherwise referred to as differential settlement). Differential settlement especially can cause problems for rigid hydraulic structures by inducing stresses that can lead to joint separation, cracking, and shear failure. Differential settlement in flow surfaces can lead to offsets that cause flow turbulence or induce cavitation.

Uniform settlement of a spillway crest structure reduces the design discharge elevation, and could result in higher discharges. Of special concern is the settlement of conduits through embankment dams or erodible foundations. If settlement opens conduit joints or causes cracking, piping or erosion into or along the conduit may result.

Embankments that are not well-compacted may experience settlement-induced base-spreading; i.e., downward movement accompanied by outward lateral movement of the embankment. Conduits through such embankments are subject to elongation, cracking, and joint separation. Conduits comprised of sections of reinforced concrete pipe sections are particularly susceptible to elongation.

Lateral spreading can also increase earth pressure against both an outlet works/spillway intake structure and a stilling basin headwall.

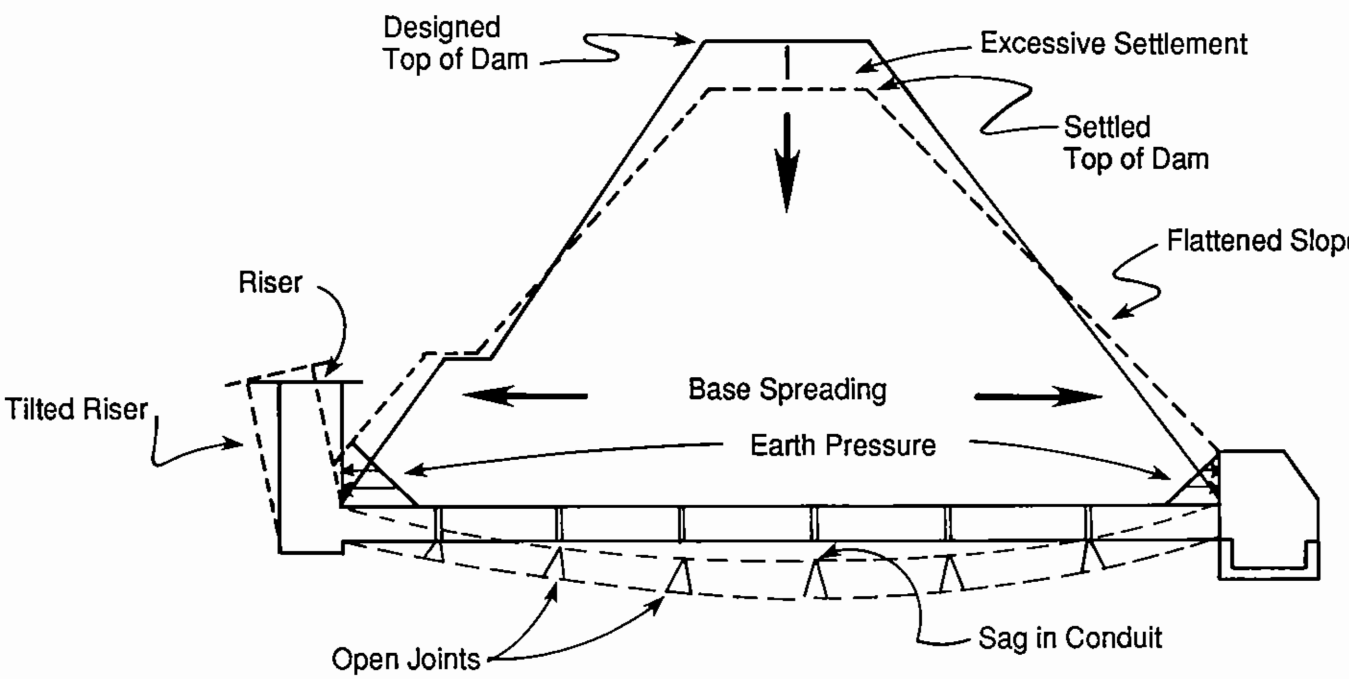
A riser may be tipped due to either severe differential settlement in its foundation or excessive earth pressure due to base spreading. A conduit placed through an embankment that settles excessively will sag. Conduit joint crowns may be cracked and joint inverts opened. Sagging also can damage conduits placed on foundations that settle excessively. These effects are illustrated in Figure I-1 on the following page.

The TADS module Evaluation of Embankment Dam Stability and Deformation contains detailed information about settlement.

I. OVERVIEW: TYPES OF HYDRAULIC STRUCTURE PROBLEMS

Settlement (Continued)

FIGURE I-1. EMBANKMENT SETTLEMENT AND BASE SPREADING PROBLEMS



HYDRAULIC FLOW PROBLEMS

Hydraulic performance can be adversely affected by poor or inadequate hydraulic design, misoperation, or unfavorable flow characteristics.

Hydraulic design usually is based upon good hydraulic performance for one specific flow condition. Hydraulic flow problems normally occur when a hydraulic structure conveys more or less than the design flow. For example, a stilling basin designed for maximum flows may not perform well for intermediate flows. The designer is obligated to consider a range of conditions, and may choose a design that gives optimum performance for somewhat less than maximum flows to better accommodate intermediate flows.

Problems can also result from improper design or from flows of different magnitude than the design flows. A spillway using a superelevated horizontal curve for the passage of supercritical flows is a good example of a design where only one flow condition will perform ideally.

I. OVERVIEW: TYPES OF HYDRAULIC STRUCTURE PROBLEMS

HYDRAULIC FLOW PROBLEMS (Continued)

Other causes of design and operation problems include:

- Departures from Standing Operating Procedures (SOP's) or incorrect procedures that result in misoperation.

- Modifications to the dam that result in changed hydraulic conditions.

Hydraulically-induced problems include:

- Cavitation
- Abrasion erosion
- Water hammer
- Vibrations

Cavitation is an unfavorable flow condition that occurs when a critical combination of the flow velocity, the flow pressure, and the vapor pressure in the water is reached. An offset or irregularity on a flow surface exposed to high velocities produces turbulence. This turbulence creates negative pressures that cause water to vaporize and form bubbles, or cavities, in the water. Bubbles collapse when subjected to higher pressures downstream from the formation site. Bubble collapse dynamics then create shockwaves that can damage the flow surface. Repetition of these high-energy shock waves eventually forms the pits or holes known as cavitation damage.

Cavitation damage can occur very quickly, because the deteriorated surface induces further cavitation. The major safety hazard from cavitation damage is the creation of holes completely through a structure and the development of a separate uncontrollable flow path.

Among common construction materials, concrete has less resistance to cavitation damage than most metals. However, metal surfaces are susceptible to cavitation damage, although stainless steel has a very high resistance. Typical sites for cavitation damage are downstream from partially open gates, gate slots, junctions, transitions, rough surfaces, and misaligned construction joints.

Abrasion erosion is the result of another unfavorable flow condition. It results from the movement of abrasive materials (granular and larger) in the flowing water. Abraded surfaces are usually smoother than cavitated surfaces. Sand, silt, and other sediment particles suspended in high velocity releases are very abrasive to flow boundaries. Like a sandblasting machine, suspended particles strike against the flow boundary and break down the bond between surface particles, accelerating the erosion process. Hydraulic jump stilling basins are especially prone to abrasion erosion.

I. OVERVIEW: TYPES OF HYDRAULIC STRUCTURE PROBLEMS

HYDRAULIC FLOW PROBLEMS (Continued)

Ballmilling is a specific form of abrasion erosion. Repeated rotation of debris (usually rocks) by discharging water grinds the surface, generally in a circular pattern. Hydraulic jump stilling basins are especially prone to ballmilling damage.

Water hammer is an oscillating pressure buildup and dropoff experienced within an enclosed conveyance. Sudden increases or reductions in discharge cause acceleration and deceleration that result in momentum reactions of the water mass. The major safety hazard is a pressure buildup large enough to burst a containment pipe, or a pressure drop low enough to collapse a pipe. In hydraulic structure design, water hammer is most common in power penstock or pumping facilities. In structures other than penstocks, changes in the rate of flow are usually regulated slowly enough to make water hammer effects insignificant.

Vibrations may occur when dynamic forces generated in flowing water become harmonically synchronized with the natural vibration frequency of a structural member. Metal structures are most subject to damage from vibrations, but even free-standing concrete walls may be affected.

Long, thin, unsupported structures especially subject to vibrations include:

- Trashrack bars
- Gate support members
- Complete gates
- Pipes

Vibrations can occur where flow velocities and direction change, such as:

- Pipe bends
- Bifurcations (junctions)
- Impact basins
- Hydraulic jump stilling basins
- Stilling wells (sleeve valves)

Other structural elements likely to experience vibrations are:

- Valves
- Valve stems and struts located in the flow path
- Gate seals
- Pumps
- Turbines
- Operating equipment
- Entire structures, such as intake towers

I. OVERVIEW: TYPES OF HYDRAULIC STRUCTURE PROBLEMS

HYDRAULIC FLOW PROBLEMS (Continued)

Normally, vibrations occur only over a limited range of discharge rates, pool levels, heads, or gate opening settings. A slight operational adjustment often can stop a vibration.

The major safety hazard from vibrations is structural fatigue and ultimate cracking and destruction of the vibrating element. The destructive nature of vibration was demonstrated vividly on the radial gates on a number of Arkansas River navigation dams. When inspected, over half of the welded connections between the supporting girders and the radial skin plate of a number of the gates were found to be broken. Without immediate emergency strengthening measures, several gates would have been destroyed and the reservoir levels necessary for navigation lost. A more complete account of this vibration problem is presented in "Spillway Gate Vibrations on Arkansas River Dams" listed with the references in Appendix B.

Metal exposed to high-velocity flows may be damaged by the process of cavitation as well as by erosion-corrosion triggered by abrasive material in the flows. Directional pits and grooves are signs of erosion-corrosion and cavitation.

EROSION

Spillway channels often are situated in earth cuts. Erosion caused by flowing water or rainfall runoff can damage the side slopes of these channels and cause flow problems in the channels. Scour of armoring and bed materials downstream of energy dissipators is a common problem.

Rainfall Runoff

The channel side slopes should be constructed on grades that are flat enough to prevent runoff erosion. A properly designed and maintained slope has a uniform surface that permits uniform or sheet flows that are less conducive to erosion than concentrated flows.

Concentrated surface runoff can produce deep erosion gullies on the slopes. These gullies can contribute to erosion of the channel during discharges.

Hydraulic structures often pass through excavated channels with cut slopes higher than the walls of a structure. The downstream channels often have cut slopes on each side of the channel. Erosion of the cut slopes results in washing of materials into the channel, blocking the channel and possibly causing structural damage.

In sheet erosion, soil losses are in uniform layers that resemble removal of pages from a tablet. Slopes with oil disturbed by equipment operation are most affected. If erosion occurs, sedimentation will follow. Sediment from sheet erosion of slopes above channels will often be deposited in channels.

I. OVERVIEW: TYPES OF HYDRAULIC STRUCTURE PROBLEMS

Rainfall Runoff (Continued)

Transport of sediment results ultimately in sediment deposits that damage or cause problems in hydraulic structures by restricting flow capabilities and reducing reservoir capacity.

Fill often serves to support a hydraulic structure such as a channel wall. Erosion of fill material may lead to failure of the structure unless the erosion is corrected.

Discharges

Erosion caused by discharge flow, or scour, is commonly associated with the entrance and return channels adjacent to rigid structures such as conduits, pipes, tunnels, penstocks, tailraces (powerhouse return channels), and stilling basins. Erosion tends to develop cavities beneath and along the upstream and downstream edges of these structures, eventually causing loss of support and failure. Scour downstream of stilling basins is probably the most common problem of hydraulic structures. The scour removes the downstream armor and bed material and can undermine the stilling basin.

Due to infrequent operation, auxiliary spillway discharge channels often have limited protection against scour. When spillway flows occur, the major safety hazard is for flows to erode the materials from the discharge channel deep enough to breach the reservoir and create a major flood wave downstream.

If the channel floor contains paths formed by animals or equipment, discharge flows will be concentrated in the paths that tend to start erosion. Head-cutting and possible loss of the channel may result from the erosion.

CONCRETE DEFICIENCIES

Hydraulic performance may be affected by deficiencies in concrete conveyance structures that prevent those structures from functioning as intended.

Causes of concrete deficiencies that can affect hydraulic performance are:

- Freeze-thaw action
- Faulty concrete mixes
- Faulty construction
- Thermal stress
- Chemical attack
- Corrosion of reinforcing steel
- Impact damage

I. OVERVIEW: TYPES OF HYDRAULIC STRUCTURE PROBLEMS

CONCRETE DEFICIENCIES (Continued)

Freeze-thaw action damages concrete when expansion of freezing water exerts internal pressure within the concrete. A concrete surface will then crack and spall, leaving a roughened surface.

Damage can also result when water standing within the joints of a structure freezes and thaws. Frost in the foundation can cause differential movement of a structure. Trashracks can be distorted or destroyed by ice pressure on frozen reservoirs.

Faulty concrete mixes can result in structures that fail to meet design strength and are subject to extensive cracking and rapid deterioration from various causes.

Faulty construction practices including under or over vibration of placed concrete, allowing fresh concrete to freeze, improper curing, and a host of other poor practices generally leave the concrete in a weakened condition, and more susceptible to physical or chemical attack. Another problem, form slippage, can leave offsets into or away from flows that can result in cavitation.

Thermal stresses result from expansion or contraction of the concrete due to temperature changes either due to air temperature changes or the heat of hydration of the cement in the concrete. These stresses can result in cracking of the concrete that may lead to further deterioration.

Chemical attack may be caused by deficiencies in concrete ingredients, such as alkali reactive aggregate, or by exposure of concrete surfaces to chemical agents.

Corrosion of reinforcing steel can occur when surface water penetrates through cracks. Corrosion of the embedded steel results in expansion and further cracking, spalling, and deterioration.

Impact damage is the spalling that results when debris or rock strikes concrete surfaces fracturing the surface.

Refer to the TADS module Identification Of Material Deficiencies for more information about concrete deficiencies.

METAL DEFICIENCIES

Other than hydraulically-induced problems, problems associated with metal structures are generally caused by corrosion in one form or another. Corrosion is the deterioration of a metal by reaction with its environment.

Chemical properties of water collected in the reservoir storage area can react with metals and cause corrosion. Water dissolves salts and other compounds during flows through natural minerals. Other corrosive elements are picked up from agricultural fertilizers or industrial waste disposal.

I. OVERVIEW: TYPES OF HYDRAULIC STRUCTURE PROBLEMS

METAL DEFICIENCIES (Continued)

Metal parts of hydraulic structures, such as piping systems, valves, gates, pumps, turbines, and associated operating equipment, are common victims of corrosion.

Corrosion in pressurized pipelines can eventually lead to pitting, pinhole leaks, or sudden rupture of the metal.

Refer to the TADS module Identification Of Material Deficiencies for more information on metal deficiencies.

UNIT II

REVIEW AND EVALUATION OF PROJECT DATA

II. REVIEW AND EVALUATION OF PROJECT DATA: OVERVIEW

INTRODUCTION

This unit will guide you in reviewing and evaluating project data relative to hydraulic structures. The following types of data will be discussed:

- Design and construction data
- Instrumentation records
- Past inspection reports

SIGNIFICANCE OF PROJECT DATA

Hydraulic structures are integral functioning components of a dam. The data file for a dam provides valuable background information to support your observations and analysis.

Reviewing the project data provides information on:

- The type of dam and hydraulic structures to be evaluated
- The design assumptions and intent
- The methods of analysis, including modeling
- The construction methods, any problems encountered, and how they were resolved
- The historical performance of the dam and hydraulic structures and the range of loading (hydrologic events) experienced

Reviewing this information before conducting field investigations and data collection will make it possible to identify specific conditions that may affect the safety of the dam and enable the field investigations to be more focused. Data review also provides a basis for evaluating the adequacy of factors of safety. As-built design and construction information should be evaluated by comparison to current state-of-the-art practices and regulatory requirements. The effects of any changes to hydrologic and seismologic loadings should be assessed.

Hydraulic structures are generally designed to operate within certain constraints to meet original project purposes. Over time, user needs may change and project purposes may be adjusted. Over the life of a project, new purposes such as hydropower may be added, water supply storage may be expanded, or new environmental constraints may alter operation procedures or require new control facilities. At times, structures may be abandoned rather than repaired and their purposes met with releases through other structures. A hydraulic structure may no longer be used because it fails to meet standards for accuracy of control, capacity, or water quality required for environmental purposes. A structure that is abandoned experiences little wear; however, the structure may not be reliable in the future if not exercised and maintained, because deterioration, sedimentation, or corrosion may occur.

II. REVIEW AND EVALUATION OF PROJECT DATA: OVERVIEW

SIGNIFICANCE OF PROJECT DATA (Continued)

When you see operational changes reflected in project data, note whether the hydraulic structures are currently being operated within design parameters. Changing project procedures can also result in less reservoir volume for flood storage and a higher risk of dam overtopping and potential failure.

II. REVIEW AND EVALUATION OF PROJECT DATA: DESIGN AND CONSTRUCTION DATA

INTRODUCTION

A review of design and construction data should begin with the following items:

- Site conditions (geologic)
- Hydrology
- Design records
- Construction records

As you proceed, you may discover that some items will require more detailed review than others, and that the relative importance of these items will vary from project to project.

The reservoir volume required to satisfy project purposes determines such factors as depth of impounded water, outlet works capacity, and plan of operation. Local topography and geotechnical concerns may have dictated the configuration and dimensions of hydraulic structures designed for a specific project.

The plans specify the type, size, capacity, control features, and energy dissipation features of all hydraulic structures such as spillways, outlet works, penstock conduits, tunnels, chutes, sluices, and pipes.

Note the key elements of the design, especially critical features and acknowledged (or clearly inferred) risks taken. Collect information about the use of similar designs under similar conditions.

An incident involving a hydraulic structure often triggers an investigation to determine the causes. Review of project data offers background information that is invaluable for understanding an incident.

Evaluate the design to determine whether sufficient basic data were collected by surface reconnaissance, surveys, subsurface investigations, material testing, hydrologic studies, and/or other special studies to furnish an adequate basis for design.

Determine whether:

- Data reveal all pertinent site and hydrologic conditions.

- Data quality is sufficient to allow confidence in assumptions and approximations made in establishing design criteria.

- The quantity and quality of data collected meet the current regulatory guidelines or the guidelines of your agency or organization.

II. REVIEW AND EVALUATION OF PROJECT DATA: DESIGN AND CONSTRUCTION DATA

INTRODUCTION (Continued)

If you conclude that the original design of the project was based on insufficient hydrologic or geologic and soil mechanics data, determine:

- Whether sufficient data have since been collected for reassessment consistent with current state-of-the-art design procedures.
- What actions would be required to obtain the needed information or data.

SITE CONDITIONS

Site conditions are the unique topographic and geologic nature of the site, the character of the earthen materials, and environmental factors, such as water quality. In reviewing hydraulic adequacy, you need to know that there are site conditions that might affect hydraulic performance, such as:

- Foundation conditions conducive to differential settlement.

  Non-uniform foundation conditions and changes in foundation material or conditions result in differential settlement of hydraulic structures, often leading to movements, open joints, and cracks. Changes in foundation density without an obvious change in foundation material also may result in differential settlement. For example, abrupt changes in density of uniform foundation materials can occur without an apparent change in the material. As less dense materials consolidate more than denser layers, differential settlement and embankment cracking may affect hydraulic structures.

- Landslides and rockfalls that could block hydraulic structures and impede flow.

For discussion of these conditions, refer to the TADS module Inspection Of The Foundation, Abutments, And Reservoir Rim.

HYDROLOGY

A common cause for dam failure is the occurrence of a flood of such magnitude so as to exceed the dam's design storage, discharge capacity, and freeboard. The occurrence of such a flood would overtop the dam. Many older dams were designed on the basis of outdated methods for estimating the design flood or insufficient hydrometeorological records. Modern methods for determining the appropriate design flood and the benefit of longer hydrometeorological records for watersheds may predict a flood of such magnitude that the dam would be overtopped.

II. REVIEW AND EVALUATION OF PROJECT DATA: DESIGN AND CONSTRUCTION DATA

HYDROLOGY (Continued)

For an embankment dam, overtopping is generally assumed to lead to an erosional failure. While concrete dams can resist flow velocities that would cause erosional failure of an embankment dam, overtopping flows may erode the abutments and foundation at the toe of the dam. Significant loss of material at these locations could result in a loss of support and a subsequent sliding or overturning failure of the dam.

Refer to the TADS module Evaluation Of Hydrologic Adequacy for more information on hydrologic deficiencies.

The nature of the watershed is important to the evaluation of hydrologic adequacy. Topography, vegetation, and type of soil affect storm runoff for a watershed. Land use changes in the watershed resulting from urbanization or changes in agricultural practices can increase or decrease the amount of flow that hydraulic structures must convey.

For example, consider a dam constructed across a stream that originally drained a densely wooded area. If a surface mining operation denudes the area of woody vegetation, the amount of runoff will increase. The spillway would be subjected to flood flows of higher discharges and velocity than anticipated by the design. Newly constructed dams located either upstream or downstream also may affect flows through hydraulic structures. Analyzing watershed data may reveal potentially unsafe hydraulic conditions.

DESIGN RECORDS

Streamlining the configuration of water conveyances has a significant impact on the magnitude of the hydraulic forces on those surfaces. Greater refinement in surface streamlining results in lower forces and slower rates of surface deterioration. As flow velocities increase, streamlining becomes even more critical to hydraulic performance.

- Streamlined flow boundaries are needed at inlets to provide a smooth transition, free of low pressure conditions.

- On large dams, inlets for conduits, penstocks, and pipes usually have elliptically curved surfaces to minimize hydraulic losses.

- For spillways and weirs, inlet streamlining needs to be provided to assure uniform and efficient entrance conditions.

II. REVIEW AND EVALUATION OF PROJECT DATA: DESIGN AND CONSTRUCTION DATA

DESIGN RECORDS (Continued)

It is not necessary that you have a detailed knowledge of streamlining design for hydraulic structures. However, you should have a general knowledge of how flows will react to various boundary shapes so that you can predict potential problem points or identify the causes of the deterioration initiated by hydraulic forces.

In the design of hydraulic structures, boundary geometry is frequently patterned after the geometry of similar structures at existing projects. The following considerations apply to such adaptations:

- The satisfactory hydraulic performance of the original structure should be verified prior to adoption. Model studies may be acceptable.

- Some physical and operational differences always exist between sites. Though at times these differences may appear to be slight, hydraulic performances may vary significantly.

Many recent hydraulic structures have precedence for their designs. This is particularly true of dams with complex structures such as multiple-level inlet port systems.

The shapes of other hydraulic structures such as spillway crests, spillway piers, conduit inlet curves, valve and gate lips, and hydraulic jump stilling basins have been developed through prototype and model research to the point that designs may have been laid out mathematically.

Other design points include:

- An entrance channel should have a greater cross-sectional flow area than the control section.

- Sharp, angled surfaces are not desirable in the boundaries of hydraulic structures such as conduits that confine flows. Bends in water conveyances should be designed with the largest possible radii consistent with structural requirements.

- The entrance channel floor should be below the spillway crest for efficient crest operation.

II. REVIEW AND EVALUATION OF PROJECT DATA: DESIGN AND CONSTRUCTION DATA

DESIGN RECORDS (Continued)

The detrimental effects of excessive uniform settlement or differential settlement on an embankment dam and its appurtenances should be minimized by defensive design measures, such as those listed below. Embankments that are susceptible to excessive or differential settlement have an increased likelihood that conduit joints may separate, which may lead to the escape of conduit flows into the fill and subsequent erosion, or embankment materials may be carried into the conduit by seepage. Either of these conditions can lead to failure of the dam.

- Camber is the practice of adding fill to the crest above the design elevation to compensate for anticipated settlement, particularly along a spillway conduit. But too much camber may actually increase settlement and open embedded conduit joints.

- Unconsolidated foundation materials, such as stream channels filled with loose deposits, are removed.

- Abutments often are shaped with slopes of 2:1, 3:1, or flatter, and abrupt changes in slope are eliminated. Flattening of slopes has the effect of spreading subsequent embankment settlement over a wider horizontal distance.

You should review structure designs if seepage monitoring indicates there may be hydraulic pressures on the external surfaces of a hydraulic structure that may be higher than the structure is capable of sustaining. Uplift pressures not considered in the design are a major concern.

Other design features that should be evaluated for potential problems are . . .

- Steeply inclined spillway tunnels or chutes that are subject to high velocity flows. The greater the distance from the inlet to the elbow at the bottom of the inclined portion of the spillway, the greater the need for aeration to prevent potential cavitation damage.

- Discharges not directed away from the toe of an embankment. The embankment risks damage from erosion or saturation.

- Hollow jet valves on outlet works. Operation of these type valves has produced structural problems in hydraulic jump stilling basins, including:

    - Heavily damaged concrete due to rock drawn from the outlet channel into the basin to churn about and result in ballmilling damage.

    - Excessive wave action.

II. REVIEW AND EVALUATION OF PROJECT DATA: DESIGN AND CONSTRUCTION DATA

DESIGN RECORDS (Continued)

- Lack of support for adjacent upstream floor panels of a conveyance structure. The downstream floor panels should be designed to provide support for the upstream floor panels. Such support could be in the form of a keyway or cutoff attached to the upstream end of the floor panel that extends under the downstream edge of the upstream floor panel.

  The use of continuous reinforcement or dowels through joints also helps prevent movement of floor panels in relation to one another.

  Movement usually results in the failure of the downstream floor panel during the passage of high velocity flows. The impact of the water against the upstream edge of the panel along with increased pressures under the panel caused by seepage of water through the uplifted joint can cause rapid removal of the panel and eventual failure of the floor. Small movements of floor panels can also result in cavitation damage downstream.

- Auxiliary spillways situated in natural materials that pass flows only infrequently during large floods. Because of infrequent operation, the discharge channels are often designed with limited or no protection against erosion. You should assess whether the materials in the discharge channel may erode deeply enough to undermine the control section, breach the reservoir, and create a major flood wave downstream.

CONSTRUCTION RECORDS

Construction records generally can be obtained from the dam owner, the agency, or the consulting engineer responsible for overseeing construction. Contractors who perform the construction also may have records available.

In evaluating hydraulic adequacy, your major concern when reviewing construction records is to determine whether hydraulic structures were built as designed. Secondly, you should identify any problems encountered during construction and review how they were resolved.

II. REVIEW AND EVALUATION OF PROJECT DATA: DESIGN AND CONSTRUCTION DATA

CONSTRUCTION RECORDS (Continued)

If the design was somehow not reflected in the construction, note the differences. Then determine whether the difference could affect:

- **Performance**. An example of a difference that affects performance is a conduit designed with rounded corners in cross section, but constructed with square corners. The lack of streamlined surfaces intended by the design reduces efficiency and increases turbulence in the conduit as constructed.

- **Structural integrity**. Cavitation, piping, and binding of control gates are possible consequences of construction that diverges from the design. Even small changes in dimensions or materials might affect structural integrity, especially in hydraulic structures subjected to high-velocity flows.

Examine the construction records to determine why changes were made in the design. Possible reasons for changes are:

- Economics. Inferior materials or inadequate dimensions, form, or alignment are possible consequences of changes made to save money.

- To solve construction problems. Two common problems are:

    - Nonavailability of design materials. The material used may not meet the standards or needs of the design.

    - Foundation conditions. Unexpected problems with foundation conditions during construction may signal continuing problems with hydraulic structures.

- Last-minute changes in project objectives, such as:

    - Increasing or decreasing reservoir storage.

    - Adding or changing control features.

Construction records should discuss foundation conditions. Subsequent movement of the floor of a hydraulic structure could be traced to a foundation weakness, improper construction of drainage features, or foundation preparation.

Failure of a wall could be the result of poor construction practice. The aggregate sources, concrete mixes, temperatures, and methods of placement should be in the records. The records often will include discussions of construction problems that have influenced future behavior of the structure.

II. REVIEW AND EVALUATION OF PROJECT DATA: DESIGN AND CONSTRUCTION DATA

CONSTRUCTION RECORDS (Continued)

The following documents can provide valuable information about construction:

- Construction specifications
- As-built drawings
- Construction diaries, logs
- Photograph files
- Records of quality control tests
- Change orders or contract modifications

Evaluate elements of the construction operation that might have a critical bearing on potential problems. Determine whether . . .

- Construction operation was monitored by an adequate inspection program and complied with critical provisions of the contract specifications.

- Specifications were adequate for the specific installation under consideration.

If the records indicate that conditions during construction were appreciably different from those assumed in the design, determine whether the changed conditions were adequately reported to the designer, and appropriate action was taken to verify the adequacy of the design or to modify it to compensate for the effects of the actual site conditions.

If an incident has occurred at the site, look for items in the construction records that are pertinent to the failure. A hydraulic structure may have been damaged and repaired during construction. Often repairs are not as durable or complete as the original structure. Failure of a repaired structure may eventually result due to failure of the repair. In one instance, during installation of a spillway conduit, a bulldozer knocked a hole in a concrete section of the conduit. Instead of replacing the entire section, a steel patch was placed over the hole. Acidic drainage outside of the conduit corroded the patch, resulting in leakage from the conduit. The patched conduit section failed, although the remaining conduit was in good condition.

COMPARISON WITH STATE-OF-THE-ART PRACTICE

Modern practice and regulatory requirements have evolved through:

- The investigation of past problems.

- New understanding of hydraulic principles and the behavior of hydraulic structures.

II. REVIEW AND EVALUATION OF PROJECT DATA: DESIGN AND CONSTRUCTION DATA

COMPARISON WITH STATE-OF-THE-ART PRACTICE (Continued)

If available and complete, project records describe the design, analysis, and construction methods used. These methods should be compared with modern practice to determine if inherent deficiencies might exist with the hydraulic features of a dam. Implementation of advances in hydraulic theory have helped prevent some of the problems experienced in older structures.

One example of advances in the understanding of hydraulic structure performance is in the area of full-flow closure of upstream gates in metal conduits. The air demand created by such a closure must be satisfied or a vacuum may develop downstream from the gate as it is closed that could collapse an unstiffened pipe. Recognition of this potential problem today allows sufficient supplemental air to be provided by vents downstream from the type of gate configuration, or pipe stiffeners can be added.

To fully evaluate the adequacy of hydraulic structure operational performance, you must know expected discharge durations and frequency of occurrence. From a safety standpoint, the significance of hydraulic problems experienced in any discharge structure is dependent upon the frequency of use.

A spillway with a hydraulic jump stilling basin is generally designed to contain the jump at a lower discharge than at the peak discharge. If the basin is not properly designed, passage of larger flows will cause the jump to sweep out of the basin, resulting in possible erosion of the downstream channel. The significance of this problem is dependent on the frequency that peak discharges occur.

The original design capacities of appurtenances should be compared with their current operational requirements. If you find that a hydraulic structure will be operating outside its design range, you need to know the basis for the original operating range. For example, if greater releases are now required to pass a larger design flood, the increased velocity of the releases may induce a hydraulic problem, such as cavitation of control valves, or the discharges may now be higher than can be passed by the downstream channel without causing flood damage, such as bank overtopping.

II. REVIEW AND EVALUATION OF PROJECT DATA: INSTRUMENTATION

INTRODUCTION

Reviewing instrumentation data, particularly seepage flow and water quality measurements, can provide clues to potential problems involving hydraulic structures.

SEEPAGE INSTRUMENTATION

Conduits that pass through embankment dams may experience leakage either into or out of the conduit through cracks or failed joint waterstops. Such leakage upstream of the impervious core is usually not considered detrimental. Leakage within the core section of the conduit, however, can pose serious problems. If leakage is occurring into the conduit, it could transport fines from the core and lead to sinkholes and, if unchecked, eventual collapse of the dam. Leakage from the conduit into the core can cause erosion along the conduit if there is no adequate downstream filter to prevent movement of core fines.

Seepage from hydraulic structure drain holes should be evaluated. If the drain holes become clogged, pressures could build up and lead to collapse of chute or basin walls or uplift of floor slabs. Sediment passing through drain holes indicates backfill or foundation material is being piped out, and loss of support for the structure could result.

Evaluate whether seepage or leakage is increasing or decreasing with time. An increasing rate for a given reservoir elevation indicates that seepage paths are enlarging or becoming more direct, and possibly that piping is occurring. A decrease in seepage or leakage for a given reservoir elevation indicates that the seepage path may be sealing naturally. The situation should continue to be monitored, and the cause of the decrease verified.

Refer to the TADS module Evaluation Of Seepage Conditions for more information.

STRUCTURAL MOVEMENT INSTRUMENTATION

The movement of hydraulic structures can be of great significance to the overall safety of a dam, and such movements are very often detected and monitored by instrumentation. The following are examples of structural movement of hydraulic structures and the consequences:

- Movement and eventual collapse of chute or stilling basin walls could block discharges and lead to overtopping of the dam. Flows impinging on the failed wall area could also erode the unprotected abutment or embankment and undermine and fail the remaining structure.

- Uplift or settlement of chute floor slabs can leave offsets into the flow that could initiate cavitation damage if discharge velocities are sufficiently high.

II. REVIEW AND EVALUATION OF PROJECT DATA: INSTRUMENTATION

STRUCTURAL MOVEMENT INSTRUMENTATION (Continued)

- Movement and joint separation or cracking of conduits passing through embankments can lead to internal piping or erosion and failure of the dam.

- Settlement of supporting spillway gate piers could lead to binding and inoperable gates, and an inability to pass flood flows.

- Expansion of the concrete in gated spillway piers due to alkali-aggregate reactivity could also lead to binding and inoperable gates.

Instrumentation, such as surface measurement points and various crack monitoring devices, can be employed to detect or follow the progress of structural movement. The records from these instruments should be reviewed to determine the occurrence or severity of the aforementioned types of problems.

II. REVIEW AND EVALUATION OF PROJECT DATA: PAST INSPECTION REPORTS

CONDITION CHANGES OVER TIME

Review of past inspection reports is extremely important. Hydraulically induced damage to structures can occur quickly or develop slowly over many years. Rapid damage, such as erosion of an earthen auxiliary spillway, or cavitation of structures, often poses an immediate threat to the safety of the dam and requires immediate attention.

A number of other hydraulic-related problems develop slowly and require some judgment about when remedial measures are warranted. Evaluating changes in seepage or leakage rates, structural damage, erosion, corrosion, or other conditions previously reported is essential for determining when repairs should be made. Review of the periodic inspection reports of other projects with similar hydraulic facilities often can be helpful in evaluating conditions.

UNIT III

INVESTIGATION OF HYDRAULIC CONDITIONS

III. INVESTIGATION OF HYDRAULIC CONDITIONS: OVERVIEW

INTRODUCTION

In this unit, you will learn about methods of investigating the condition of hydraulic structures. Investigating hydraulic conditions involves a series of actions and decisions. The process involves one or more of the following steps:

- Inspection of hydraulic structures and operation.
- Field investigations to provide precise data on hydraulic conditions that have been observed to be potentially hazardous.
- Laboratory testing and modeling to identify deficiencies that can adversely affect hydraulic operation.

The investigation process may reveal a potentially or actually hazardous hydraulic condition. You will use the information developed during investigations in the next step of the evaluation process, described in the next unit: analyzing hydraulic conditions.

SIGNIFICANCE OF INVESTIGATING HYDRAULIC CONDITIONS

Identifying hydraulic-related structural problems and determining the type of investigations needed to evaluate and remedy such problems can be as simple as conducting an inspection or as complicated as installing sophisticated instruments to precisely measure hydraulic forces and structural responses.

When inspecting the hydraulic condition of any discharge structure, consider the quantity and quality of the flow that has been passed during the structure's lifetime. The maximum discharge, presence of sediment or corrosive elements, and total volume of flow should be determined.

It is common for auxiliary spillways at dams not to have experienced discharges. The hydraulic performance of such features cannot be evaluated through field inspections. In these cases, evaluations generally cover just structural integrity of the spillway. In contrast, some service spillways frequently make discharges, but probably still have not experienced their design discharge.

Investigation of hydraulic structure deficiencies involves a comprehensive review of suspected or apparent problems.

III. INVESTIGATION OF HYDRAULIC CONDITIONS: OVERVIEW

SIGNIFICANCE OF INVESTIGATING HYDRAULIC CONDITIONS (Continued)

The following TADS modules provide basic information to aid in problem identification and investigation:

- Inspection Of Spillways And Outlet Works

- Inspection And Testing Of Gates, Valves, And Other Mechanical Systems

III. INVESTIGATION OF HYDRAULIC CONDITIONS: INSPECTIONS

INTRODUCTION

Most observable problems with hydraulic structures can be detected during regularly scheduled inspections. But there are circumstances when special inspections or other methods, such as hydrographic surveys, must be employed to assess the condition of a dam's hydraulic features. The early detection of problems permits repairs or modification of operations that can minimize the amount of subsequent damage that otherwise may occur.

SCHEDULED INSPECTIONS

Cracking, structural movement, leakage, and erosion and cavitation damage are but a few examples of the kinds of problems that can be identified during regularly scheduled inspections. For a comprehensive discussion on identifying appurtenant works deficiencies, refer to the TADS module Inspection Of Spillways And Outlet Works. It is also highly desirable to observe the operation of a dam's hydraulic features to detect problems associated with the flow of water at an early stage before significant damage occurs. Depending on the timing, some operations may be observed during regularly scheduled inspections, typically those associated with the outlet works, but more often special inspections are necessary.

SPECIAL INSPECTIONS

Special inspections of hydraulic structures are generally necessary for several reasons. Some hydraulic features, such as stilling basins and conduits upstream from emergency gates, are normally inundated and rarely available for inspection. Hence, a special inspection should be conducted when water levels are low or have been drawn down for some reason such as routine maintenance. If these opportunities seldom occur and there is reason to suspect possible problems, either because of design or construction inadequacies or other evidence, then consideration must be given to dewatering and inspecting. However, care must be exercised in dewatering normally inundated features by such means as bulkheading without lowering the reservoir, because some structures may not have been designed to withstand the resulting pressure differences.

Because the timing of regularly scheduled inspections rarely coincides with significant flow events such as spillway operation, especially the passage of large floods, special inspections should be conducted to observe the performance of structures during, and in some cases following, these events. Such anomalies as the improper location of a hydraulic jump, excessive flow turbulence, or even the "popping" sound of cavitation may be discernible by observing hydraulic structures in operation.

III. INVESTIGATION OF HYDRAULIC CONDITIONS: INSPECTIONS

SPECIAL INSPECTIONS (Continued)

Special inspections should also follow the passage of large floods or the occurrence of a nearby earthquake to determine if any structural damage has occurred that might impair subsequent operation and threaten the safety of the dam. Cracked conduits and jammed gates are examples of seismic damage. Erosion and cavitation damage to conveyance structures, channels, and energy dissipators may result from the passage of large floods.

HYDROGRAPHIC SURVEYS

Many hydraulic structures such as stilling basins and the riprap armoring that provides scour protection in the return channel are not or cannot be dewatered for inspection. Hydrographic surveys should be performed for such structures if there is potential for erosion damage. Surveys generally are repeated at regular intervals to track changes in the underwater surfaces.

Boundaries of the area to be surveyed depend on local conditions. Once the survey area is established, a grid system divides the area into regularly spaced points where depth is measured. Ordinarily a fathometer is used to obtain measurements. However, within 20 feet of a reinforced concrete structure, the reinforcing steel interferes with fathometer readings. Soundings provide more accurate measurements at these locations.

Results of hydrographic surveys may be recorded on contour maps or comparative cross sections. Figure III-1 shows an example of a contour map, and Figure III-2 is a representative cross section. The contour map provides a comprehensive record of the survey area, but cannot be readily compared to results of prior surveys. The comparative cross section shows a limited portion of the underwater surface, but clearly reflects changes since prior surveys.

If a hydrographic survey shows that the underwater surface adjacent to a hydraulic structure has eroded below the bottom of the structure, immediate corrective action may be necessary. Inspection divers can be used to investigate the situation further.

HYDROGRAPHIC SURVEYS (Continued)

FIGURE III-1. HYDROGRAPHIC STUDY CONTOUR MAP

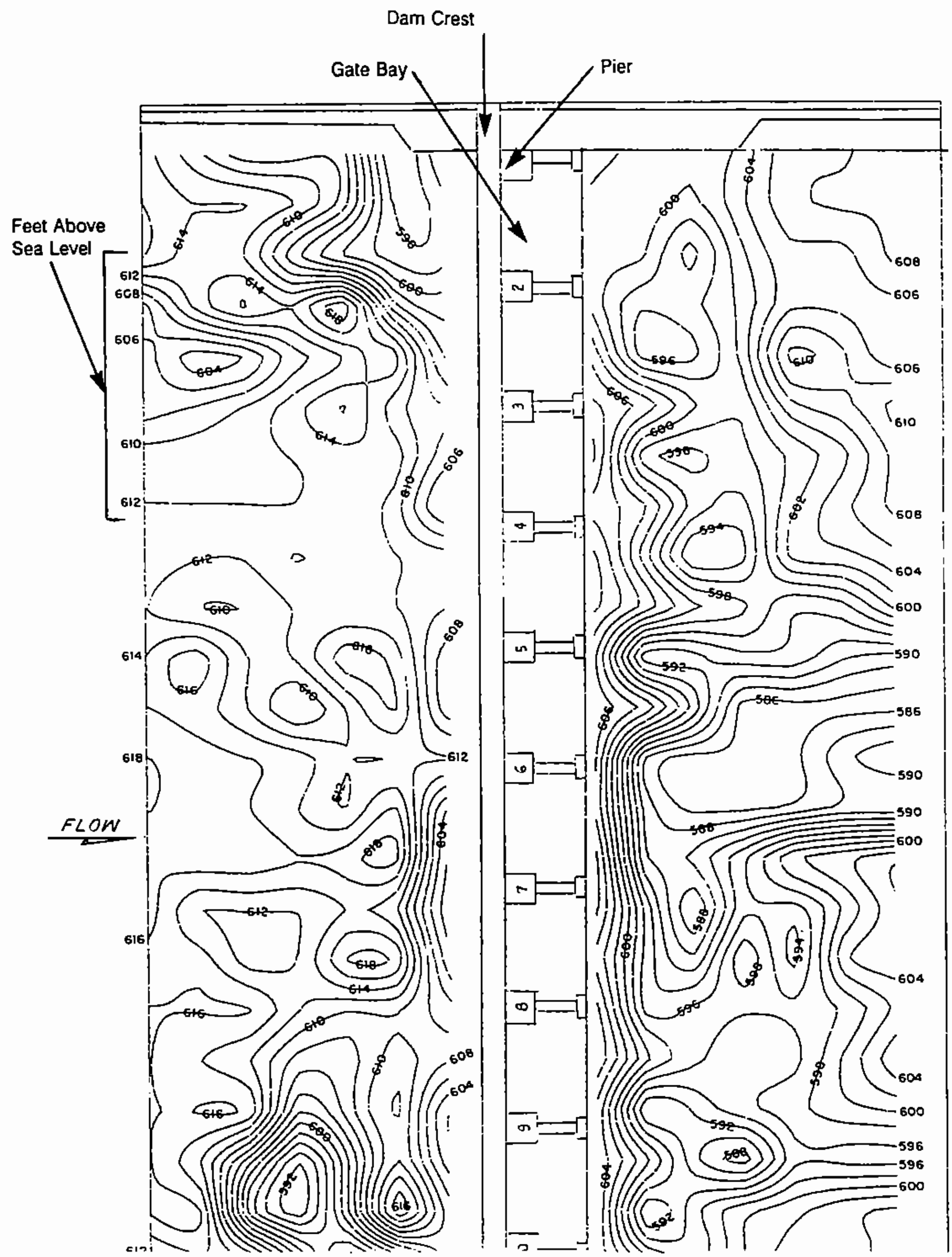
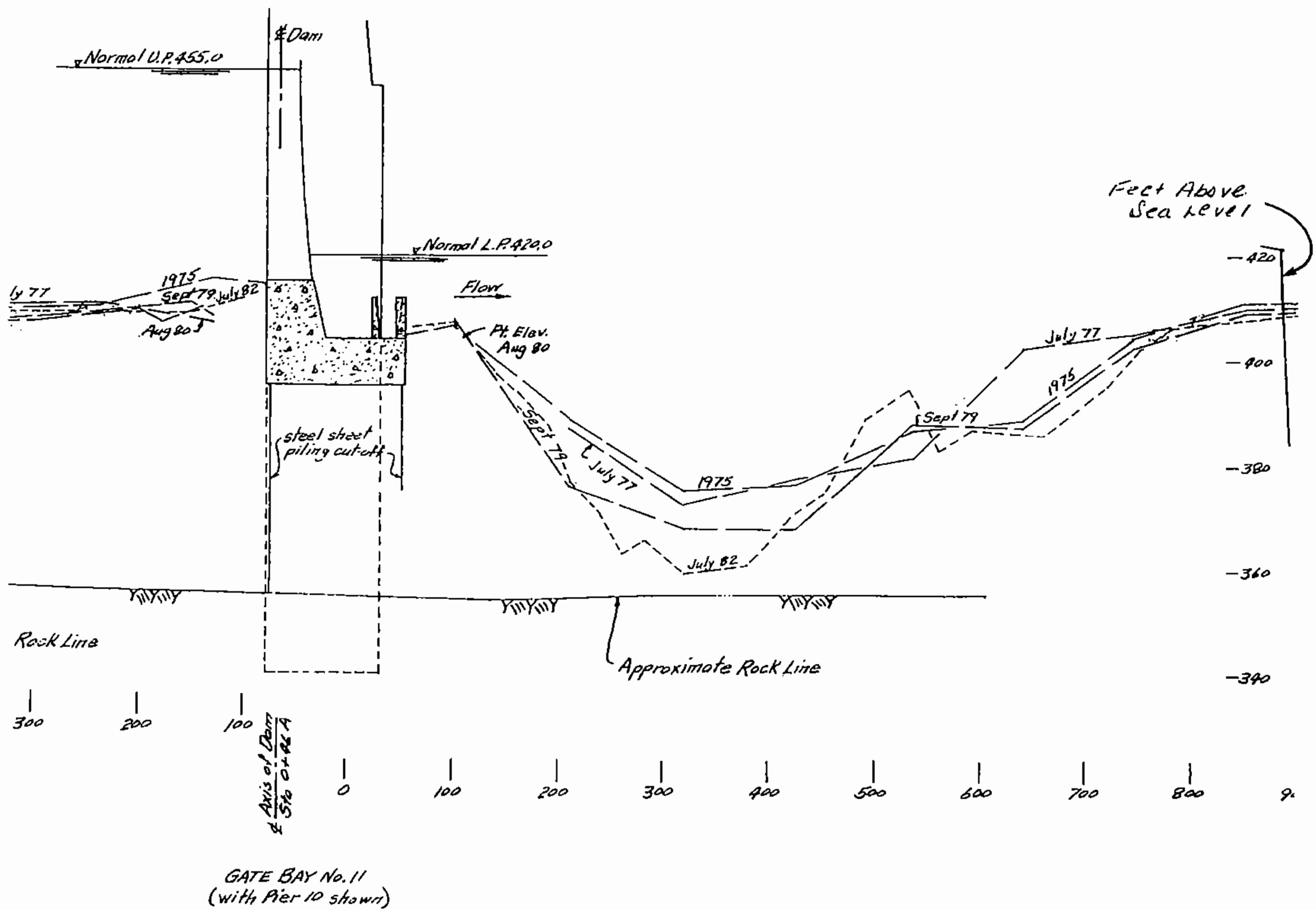


FIGURE III-2. HYDROGRAPHIC STUDY CROSS-SECTION MAP



III. INVESTIGATION OF HYDRAULIC CONDITIONS: DAMAGE INVESTIGATION

INTRODUCTION

Many agencies and organizations appoint an investigating team or committee to inspect serious damage to hydraulic structures immediately after detection. Such a team may include the following professional disciplines:

- Hydraulic engineer
- Structural engineer
- Mechanical/electrical engineer
- Construction engineer
- Geologist or geotechnical engineer
- Environmental specialist
- Surveyor

DAMAGE INVESTIGATION

If the damage might be obscured by subsequent flow of water or threaten the safety of the dam, an investigating team should be dispatched as soon as possible. Photographs or videotapes of damage should be taken soon after the occurrence.

If damage has resulted from hydraulic operations, the damaged areas should be inspected to determine actual hydraulic behavior, noting the following:

- Observe flow traces on the floor and walls. Determine if flow patterns indicate flows contrary to design.

- In the case of suspected cavitation damage, observe the area upstream from the damage for evidence, such as offsets into or away from the flow, that may have initiated cavitation. Try to distinguish between cavitation and erosion.

- Observe floor joints and wall joints to determine if there has been any unexpected movement, and determine the extent and type of movement.

Interviews with dam operators and other personnel at the dam site often provide information about hydraulic operations over a range of discharges, sometimes extending over the time period since initial construction. Such discussions can help determine if the damage may have resulted from improper operation.

A report documenting a damage investigation should include the specific location of the damage, referencing stationing, or distance from a particular feature. The damage should be shown on a map or set of drawings.

III. INVESTIGATION OF HYDRAULIC CONDITIONS: DAMAGE INVESTIGATION

DAMAGE INVESTIGATION (Continued)

Reports should also include:

- Climatological and hydrological conditions at the time damage occurred, and the estimated return interval for the event.

- Reservoir levels and flow rates through hydraulic structures at the time damage occurred.

- Detailed description of damage.

- Magnitude of damage
  - Size (length, width, and depth)
  - Capacity
  - Percent restricted
  - Structural condition

- Shape or pattern of damage

- Probable cause of damage (if determinable)
  - Excessive uplift or lateral pressures
  - Cavitation or erosion
  - Excessive settlement
  - Concrete deterioration
  - Material degradation
  - Seepage
  - Leakage
  - Restricted hydraulic flow
  - Vandalism

UNIT IV

ANALYSIS OF HYDRAULIC CONDITIONS

IV. ANALYSIS OF HYDRAULIC CONDITIONS: OVERVIEW

INTRODUCTION

If an investigation reveals a hazardous or potentially hazardous hydraulic condition, that condition must often be analyzed to confirm the hazard and determine its significance or severity. In this unit, you will look at methods commonly used to analyze hydraulic conditions at a dam.

A number of factors may affect hydraulic conditions. Techniques are available to analyze each of the following factors:

- Structural movement
- Erosion
- Concrete damage
- Cavitation and abrasion erosion
- Metal degradation
- Flow characteristics

During the course of an analysis you will reach decision points. The actions you will take depend upon whether the condition being analyzed:

- Was reported before, and if so, has worsened.

- Endangers the structure.

- Will become worse in the near future, or resulted from a single rare event.

The results of your analysis will lead to the final step of the evaluation process, described in the next unit: choosing appropriate remedial action.

IV. ANALYSIS OF HYDRAULIC CONDITIONS: STRUCTURAL MOVEMENT ANALYSIS

INTRODUCTION

Movement of hydraulic structures, either as a whole or differential movement, can cause the structures to fail. A structural movement analysis evaluates the various forces and pressures that may cause, or have caused, a structure to move from its design location.

TYPES OF STRUCTURAL MOVEMENT ANALYSES

Evaluation of the movement of hydraulic structures may involve one or more of the following types of analyses:

- **Seepage Analysis.** Seepage through a dam and/or its foundation may exert destabilizing pressures against hydraulic structures. Seepage may also develop into a piping condition and remove supporting structure foundation materials, causing a structure to fail. Refer to the TADS module Evaluation of Seepage Conditions for information about seepage analysis.

- **Earth Pressure Analysis.** The pressure exerted on a hydraulic structure by the surrounding backfill may induce sliding or tipping of the structure. Refer to any soil mechanics or foundation engineering text for information on earth pressure analysis.

- **Settlement Analysis.** Hydraulic structures located on or within embankment dams are subject to potentially damaging structural movement if the embankment experiences excessive settlement. Refer to the TADS module Evaluation of Embankment Dam Stability and Deformation for information about embankment settlement. Hydraulic structures located on other unconsolidated foundations are also subject to settlement. Refer to any soil mechanics or foundation engineering text for information on settlement analysis.

IV. ANALYSIS OF HYDRAULIC CONDITIONS: EROSION ANALYSIS

INTRODUCTION

Erosion is the wearing away of the land surface by detachment and transport of soil and rock materials through the action of moving water. Your evaluation of hydraulic conditions includes analyzing how the process of erosion affects hydraulic structures.

Begin your analysis by classifying the type of erosion you observe. The types of erosion include sheet and rill erosion and channel erosion.

Your next step is evaluating the significance of erosion. Erosion can range in significance from being a maintenance problem, to adversely affecting hydraulic performance or being a serious hazard to a hydraulic structure and to the safety of the dam.

After examining the type and significance of existing erosion, proceed to determine erosion potential, or the predicted rate of erosion at or near hydraulic structures under steady and unsteady flow conditions. An important factor in determining erosion potential is the erosion resistance of materials subject to erosion.

TYPES OF EROSION

There are two basic types of erosion: sheet and rill erosion and channel erosion.

Sheet And Rill Erosion

Sheet erosion is the uniform soil loss from an area by raindrop splash and overland flow. Associated with sheet erosion are the numerous but conspicuous small channels or rills caused by minor concentrations of runoff. By definition, rills are no more than 30 cm in depth. Larger water channels are gullies. Unlined water conveyance channel slopes and surrounding slopes are subject to sheet and rill erosion.

The basic factors affecting sheet and rill erosion are:

- Rainfall
- Material properties
- Slope length
- Slope steepness
- Condition and kind of protective cover

The efficiency and capacity of water conveyance channels decreases as sediment eroded from surrounding slopes collects in the channels. If a dam is located in a watershed where farming has resulted in significant areas of erosion-prone cultivated soil, rapid sediment buildup may adversely affect hydraulic performance.

IV. ANALYSIS OF HYDRAULIC CONDITIONS: EROSION ANALYSIS

Sheet And Rill Erosion (Continued)

Problems caused by sheet and rill erosion in small watersheds generally are analyzed using the Universal Soil Equation, which computes an estimate of erosion based on values of the factors listed. Predicting Rainfall Erosion Losses, Agricultural Handbook 537 listed in Appendix B, describes the Universal Soil Loss Equation.

Channel Erosion

Channel erosion is the removal of channel bank and bed materials by the force of flowing water and the caving of channel banks, resulting in enlargement of the channel section.

The basic factors affecting channel erosion are:

- Bed slope or energy gradient
- Discharge velocity and flow characteristics
- Material properties
- Channel geometry
- Condition and kind of protective cover

Methods of determining soil loss by the various types of channel erosion are:

- Comparing aerial photographs from different dates to determine the change in channel sizes and alignments.
- Resurveying established cross sections to determine the difference in total channel cross-sectional area.
- Assembling historical data to determine major long-term shifts in channel alignment.
- Conducting field studies to estimate the change in channel size (volume per unit length of channel).

Formulas used to compute channel erosion can be found in Section 3, Chapter 3 of the National Engineering Handbook listed in Appendix B.

IV. ANALYSIS OF HYDRAULIC CONDITIONS: EROSION ANALYSIS

EVALUATING THE SIGNIFICANCE OF EROSION

If you observe erosion of unlined channels and structural fill, consider the following factors in evaluating the significance of the erosion:

- Has the erosion been reported before? Since erosion can progress rapidly, monitor the affected area closely after erosion is first reported until the rate of material loss can be established.

- If previously reported, is the erosion worse than when last reported? If the erosion is worse, determine how great a change has occurred, and what events might have aggravated the erosion.

- How likely is the damage to get worse in the near future? The erosion may have resulted from a series of ordinary storms or from a design flood that has a very long return interval.

- Does the erosion endanger the structure? If the structure may fail, remedial action should be considered immediately.

The potential for erosion that would adversely affect hydraulic structures or performance must be evaluated. In order to check the erodibility of emergency spillway channels and areas where water seldom flows, soil samples can be collected and subjected to erosion tests in a laboratory. Photographs and cross-sectional measurements over a period of time will help you identify erosive trends and rates.

DETERMINING EROSION POTENTIAL

For water conveyance structures with uniform cross-sectional geometry carrying steady-state flow, velocity provides a fairly reliable correlation to the erosion potential.

Another factor used to measure erosion potential is the tractive force or shearing force that develops between the flow and flow boundary. This force is expressed in pounds per square foot of boundary area. However, when flows are unsteady, turbulence, surges, and wave action increase the erosion potential.

Guidance on the design and potential performance of erosion-retarding measures is limited for unlined spillway channels. Performance is particularly dependent on the specific type of natural materials in the channel. Although the resistivity of these materials cannot be accurately modeled, the hydraulic performance of the structures can be checked in a physical modeling facility and may be helpful in identifying points of maximum erosion.

IV. ANALYSIS OF HYDRAULIC CONDITIONS: EROSION ANALYSIS

Erosion Under Steady Flow Conditions

Average velocity is the value normally used to estimate erosion potential. Of the erosion factors mentioned, velocity is the simplest to identify, either through measurement or by computation. Instruments that measure velocity normally provide a reading at one specific point within the flow cross section. A series of point measurements throughout the cross section will provide the data needed to determine average velocity.

Plots of velocity profiles that develop within a particular cross section illustrate the relationships between the average, peak, and specific point velocities. Examples of flow velocity profiles for a number of typical cross-sectional shapes are presented in Internal Flow Systems (referenced in Appendix B).

For free surface conveyances, velocities also depend on the longitudinal slope and the surface roughness of the conveyance. These factors establish a velocity-depth relationship for any specific discharge. As mentioned above, reliable velocities can be computed only where flows are relatively steady over time, and the cross-sectional shapes are relatively uniform in relation to conveyance length.

Formulas for computing velocities in conduits or channels are presented in most hydraulic textbooks. Three examples from Appendix B are Handbook of Hydraulics, Chapter 2 of Engineering and Design, Hydraulic Design of Reservoir Outlet Works, and Open Channel Hydraulics. Open Channel Hydraulics also provides guidance in selecting appropriate roughness values for a wide variety of construction materials.

Erosion Under Unsteady Flow Conditions

Hydraulic structures often contain variations in boundary geometry that can result in unsteady, highly turbulent flow conditions. Bends, transitions, valves, junctions, and hydraulic jump stilling basins are typical examples of such structures. Within these regions, velocity alone is not an accurate measure of erosion potential. Turbulence, fluctuations in flow momentum, and pressure surges affect the erosion potential. Erosion potential increases with abrupt changes in geometry of the water passage or with discharge increases. Most hydraulic research on the performance of such structures has been for specific project facilities, and the results have not been adaptable to computational procedures for general facility design.

IV. ANALYSIS OF HYDRAULIC CONDITIONS: EROSION ANALYSIS

Erosion Under Unsteady Flow Conditions (Continued)

The following are descriptions of a few approaches to evaluating erosion potential through these highly turbulent regions:

- Determine flow conditions through comparison with existing structures that have similar features and for which performance characteristics are already known.

- Research the records of hydraulic laboratories for model tests that may have been conducted to check the performance characteristics of other structures with similar features. Most laboratories maintain published lists of research studies conducted and reports prepared.

- Contact hydraulic laboratories to determine the types of research conducted. Contract with an appropriate laboratory to construct a physical model study of the facility to check out the performance characteristics and make design adjustments as needed to provide satisfactory performance.

EROSION RESISTANCE

All natural and manmade materials that serve as boundaries for flowing water eventually experience some degree of deterioration from erosion. The objectives of hydraulic structure design include:

- Constructing release facilities from materials that experience a slow rate of erosion.

- Shaping release facilities so that the boundaries are subjected to a practical minimum of erosive forces.

Considerable research has been conducted to evaluate the resistivity of various materials to erosion under steady flow conditions. From this research, a series of mathematical relationships has been developed to predict erosion resistance.

Few procedures are available to determine the resistivity of materials to unsteady, turbulent flow. No physical parameters have been identified to relate these flow conditions to erosion potential. Data on the erosion resistance demonstrated by various materials that have been used in existing projects under similar conditions provide the best guidance. Unfortunately, performance data on projects with similarly designed hydraulic structures that have been subjected to similar flow conditions seldom are available.

EROSION RESISTANCE (Continued)

Physical model studies can be helpful in reproducing the flow conditions experienced with a particular facility design, but the ability to accurately model the resistivity of materials is questionable.

Numerous types of energy-dissipating materials placed on the slopes of dam embankments and dikes have been tested in model facilities to determine resistance to wave action. Typical materials tested include a wide range of riprap blanket gradations, soil cement, roller-compacted concrete, gabions, and other embankment covers.

Natural Channel Materials

Natural channel materials are natural materials other than excavated rock. Early research on the resistance of natural materials is described in "Permissible Canal Velocities" listed in Appendix B. Fourteen types of natural materials exposed by the construction of an excavated canal were tested. Material sizes ranged from fine sands to cobbles. In the tests, the materials were subjected both to clear water and to sediment-laden water under steady-flow conditions. Maximum permissible velocities varied from 1.5 to 6.5 feet per second.

In Chapter 7 of Sediment Transport Technology listed in Appendix B, the findings from those early tests are evaluated and compared with results of several analytical procedures that have been developed to predict resistivity of materials.

The resistance of many natural materials used in dam construction normally can be increased through mechanical compaction or the addition of vegetative cover.

Many channels excavated through natural rock outcrops have remained relatively fixed. Actual resistance of these materials depends upon density, thickness, weathering tendencies, and natural fracturing tendencies.

Although some formations may be denser than concrete, little control can be exercised over smoothness or fracturing of the surface. Therefore, based on information presented in Engineering And Design, Hydraulic Design Of Flood Control Channels listed in Appendix B, soft sedimentary sandstones and limestones generally should not be expected to resist velocities greater than 20 feet per second. However, based on actual exposure to high-level spillway discharges, some rock formations have shown an ability to resist velocities nearly double these values for short time periods without experiencing excessive erosion.

IV. ANALYSIS OF HYDRAULIC CONDITIONS: EROSION ANALYSIS

Graded Riprap

The most common method of increasing the erosion resistance of earthen channel side slopes is to add a protective blanket of graded riprap. Engineering and Design, Hydraulic Design of Flood Control Channels, listed in Appendix B, provides standards for the quality, size, shape, and gradation of riprap. This manual also presents a procedure for computing the size and thickness of channel riprap required to resist imposed flow velocities. A more recent and simpler procedure for designing channel riprap is described in Stable Riprap Size For Open Channel Flows, also listed in Appendix B.

A practical limit for the use of graded riprap would be as protection against maximum velocities in the range of 15 to 17 feet per second. At these velocities, the required rock sizes and thicknesses become so large that other types of protection normally are less expensive.

Concrete

For hydraulic structures that release flows at velocities greater than 20 feet per second, formed concrete is commonly used for containing the flows because of its durability. Depending on quality and smoothness of finish, concrete has successfully withstood velocities of over 100 feet per second. In this upper range of velocities, free surface flows generally absorb large amounts of air to cushion the velocity effects. Cavitation and abrasion can contribute significantly to surface deterioration under these flow velocities.

Steel

Whenever very high velocity flows must be subjected to tight bends, transitions, junctions, discharge control valves, or gate slots, the smooth streamlining is interrupted and flow impacts with the boundaries are increased. Steel surfaces are normally more resistant than concrete surfaces due to their density, smoothness, and resilience. Usually the steel surface is in the form of steel plates or a steel casting that has been anchored to a concrete mass. In situations where the metal surface is subject to corrosion, stainless steel usually is more durable because the surface resists pitting from corrosion and cavitation forces.

Other Materials

A number of other construction materials are available to help control erosion, including:

- Gabions
- Precast concrete blocks
- Concrete-injected fiber mats
- Soil cement
- Geotextiles

These materials provide a means of protecting the in-place soils. All of the materials listed above have been used with varying degrees of success and cost savings have frequently been realized. A significant problem in use of these materials is lack of a rigorous design basis for determining resistance to imposed hydraulic forces.

IV. ANALYSIS OF HYDRAULIC CONDITIONS: CAVITATION AND ABRASION EROSION ANALYSIS

INTRODUCTION

Cavitation and abrasion erosion are two dynamic processes that cause damage to concrete flow surfaces by removing portions of the surfaces. The damage is often similar in appearance, particularly at an early stage, but cavitation is potentially a much more serious problem, and therefore it is important to be able to distinguish between the two. Generally, erosion damage is more uniform in depth, while a cavitated surface is pitted with rough, ragged holes. Popping and cracking noises (crepitation) from collapsing vapor bubbles can sometimes be heard when cavitation is occurring. Sampling the discharge water and checking for suspended sediments will give an indication of whether observed damage has been caused by erosion.

Many hydraulic conduits combine conditions that are likely to result in cavitation. Pressure profiles through conduits will identify low-pressure points. However, these profiles will not identify pressures in the reaches of flow separations or turbulence in the following locations:

- Sharp bends
- Junctions
- Expansions
- Gate slots
- Partially open valves

Chapters 2 through 5 of Internal Flow Systems listed in Appendix B explain and illustrate the flow conditions through these fittings and identify common points of cavitation occurrence. Chapter 6 of Internal Flow Systems presents the relationship between the factors that induce cavitation and examples of computation of those factors.

If the damage is abrasion erosion related, studies should be made to determine the source, nature, and amount of abrasive materials present so that effective methods of control can be applied. If the concrete is likely to continue to deteriorate, repair might be unwise, and replacement of the entire structure may be necessary. Analysis of deteriorated concrete may include:

- Mix design analysis to detect faulty concrete mixes
- Chemical analysis to diagnose chemical attack

These techniques are described in the TADS module Identification of Material Deficiencies.

Some concrete structures, especially hydraulic jump stilling basins and impact basins, are subjected to such severe, continual hydraulic loading that maintenance of concrete surfaces should be anticipated. In such cases, regular repair programs to perform such measures as filling scoured cavities during scheduled dewatering inspections may keep such structures in safe operating condition.

IV. ANALYSIS OF HYDRAULIC CONDITIONS: CAVITATION AND ABRASION EROSION ANALYSIS

MODEL STUDIES

Physical model studies should be considered to check and adjust the shapes of all release facilities that have both questionable performance characteristics and the potential for serious erosion and cavitation problems.

A hydraulic model of a structure should be constructed as it exists, including all settlements and offsets. Instrumentation should be used to determine pressure changes that could be responsible for cavitation. The model studies could be used to determine corrective action on the structure.

CAVITATION ANALYSIS

Areas susceptible to cavitation such as floor offsets, surface depressions or openings, and unventilated outlet gates can be analyzed without the use of model studies. The relative potential for cavitation occurring at a site is computed as a **cavitation index**. The sizes of the offsets, depressions, or openings are measured. The cavitation index, as presented in Cavitation in Hydraulic Structures listed in Appendix B, can be calculated using the measurements and the flow velocity. If the cavitation index indicates that the potential for cavitation is high, corrective action or performance of model studies may be warranted.

IV. ANALYSIS OF HYDRAULIC CONDITIONS: METAL DEGRADATION EVALUATION

INTRODUCTION

The condition of pipelines, radial gates, and other metal features of hydraulic structures can be evaluated through corrosion and vibration studies.

CORROSION STUDIES

The area and depth of corrosion should be recorded for future comparison and to determine the extent of the damage. Metal corrosion should be analyzed as follows:

If Corrosion Type Is . . .	You Should . . .
Pitting	Measure pit depth and describe extent.
Erosion and Cavitation Corrosion	Look for directional pits and grooves on surfaces exposed to turbulence. Describe affected areas.
Surface Galvanic Corrosion	Obtain samples for analysis.
Stress Corrosion Cracking and Corrosion Fatigue	Remove coupons (rectangular patches) for structural testing.

Refer to the TADS module Identification Of Material Deficiencies for more information about metal corrosion.

VIBRATION STUDIES

A void or abrupt change in a metal structure may induce vibrations. Some mechanical devices subject to vibration, such as exposed pipes, valves, and radial gates, can be observed during operation. Touching the devices during operation will indicate whether vibrations are occurring. Recording equipment can be used to determine the frequencies of the vibrations. Gages may be used to measure strains and stresses within the equipment.

Other devices, such as struts inside a flow passage, cannot be observed during operation. Visual inspection is required to detect evidence of vibration deflections, such as discoloration of the metal or cracking of the protective coating.

If there is concern that vibrations have affected the strength of the metal, coupons can be taken for structural testing.

IV. ANALYSIS OF HYDRAULIC CONDITIONS: METAL DEGRADATION EVALUATION

VIBRATION STUDIES (Continued)

Analysis of vibrations can identify critical combinations of gate settings, reservoir elevation, and tailwater that result in maximum vibrations. Remedial efforts can then focus on altering gate settings or other factors.

For a description of techniques used to analyze a vibration problem, refer to "Spillway Gate Vibrations on Arkansas River Dams," listed in Appendix B.

IV. ANALYSIS OF HYDRAULIC CONDITIONS: HYDRAULIC FLOW STUDIES

INTRODUCTION

Analysis of flow conditions through appurtenant structures of dams requires a basic knowledge of hydraulic engineering. Procedures have been developed over the years to perform flow analyses.

Mathematical formulas and procedures are the primary method used to approximate the movement of water through hydraulic structures and to evaluate the forces generated.

However, some hydraulic structures are too complex to allow their performances to be simulated using mathematical procedures. For these structures, an alternate method of analysis is to conduct a physical model study of the facility. The performance of water flowing through small-scale models has been found to accurately simulate the performance of the completed structures.

MATHEMATICAL ANALYSIS

Following are some of the common mathematical procedures used in the design and operation of hydraulic structures.

- **Flood routing through reservoirs.** For preliminary and final dam designs, these computations determine the peak discharges through hydraulic structures and reservoir elevations resulting from the design flood. The computations also indicate reservoir volumes and water levels attained for floods of particular frequencies. Three computer programs developed to conduct reservoir flood routings are:

    - HECI (Army Corps of Engineers)
    - TR 20 (Soil Conservation Service)
    - FLROUT (Bureau of Reclamation)

- **Conduit and spillway discharge rating curves.** Formulas have been developed to compute discharge rating curves for spillways and outlet works used to make reservoir releases. These formulas generally are used to estimate the friction losses that occur between the flowing water and the structural boundaries. Appendix B lists many publications that describe the mathematical procedures used by various agencies to compute discharge rating curves.

IV. ANALYSIS OF HYDRAULIC CONDITIONS: HYDRAULIC FLOW STUDIES

MATHEMATICAL ANALYSES (Continued)

- **Energy dissipator design analyses.** Water stored to great depths in reservoirs develops high potential energy levels. When releases are made downstream, this energy is converted into high velocities and flow turbulence. The energy must be dissipated prior to releasing flows into the tailwater or downstream discharge channel to avoid excessive erosion. Energy dissipator structures accomplish this need. References that describe mathematical analyses to evaluate designs of energy dissipators are listed in Appendix B.

- **Tailwater and downstream channel water surface profiles.** The tailwater level in the return channel greatly affects the performance of many types of energy dissipators. Degradation of the channel will lower tailwater levels and generally reduce dissipator effectiveness. Properly designed discharge structures will operate effectively even at the maximum channel degradation anticipated during the life of the dam facility. Water surface profiles in return channels are generally determined by backwater or flowline computations. Computer programs commonly used to calculate water surface profiles are:

  - TR-61, WSP II (Soil Conservation Service)
  - HEC II (Army Corps of Engineers)
  - E3WSP (Bureau of Reclamation)
  - PROFILE: Water Surface Profiles--Cavitation, Air Entrainment, Bends, Offsets (Bureau of Reclamation)

PHYSICAL MODEL ANALYSIS

Dams that have unusual flow discharge requirements often require special hydraulic release structures. Generally, design precedents for such structures are not available. In such cases, the best design procedure is to conduct physical model studies of the structures. In addition to the development of initial designs, model studies are often used to design corrections to hydraulically unsatisfactory features of existing structures. Also, the designs of hydraulic structures that are proposed as additions to existing facilities can be analyzed and improved through the use of physical models. A partial listing of laboratories that regularly conduct physical model studies is provided in Appendix C of this module.

UNIT V

REMEDIAL ACTION

V. REMEDIAL ACTION: OVERVIEW

INTRODUCTION

This unit will introduce you to:

- Emergency and temporary actions to deal with hydraulic deficiencies, including:
  - Restricting reservoir elevation
  - Restricting discharges
  - Revising operating procedures
  - Protecting and stabilizing damaged areas

- Long-term measures to deal with hydraulic deficiencies, including:
  - Reconstructing, modifying, or stabilizing structures
  - Providing erosion protection
  - Removing or trapping sediment
  - Repairing or protecting concrete
  - Constructing aeration devices
  - Removing surface irregularities
  - Providing corrosion protection
  - Adding pressure relief systems

- Procedures for monitoring corrective actions

HAZARD EVALUATION

Once a hazard condition has been detected in a hydraulic structure at a dam, the primary concern is the immediacy and magnitude of the consequences posed by the condition.

Subsequent evaluation of the condition may conclude the following:

- Immediate temporary corrective action should be implemented, followed by a comprehensive study to seek a more permanent solution.

- A permanent solution can be easily implemented. (For example, a change in operational procedures may eliminate the hazard.)

- Periodic maintenance of the hydraulic structure will be necessary, and is an acceptable economic alternative.

- Remedial action should be postponed until the situation reoccurs or worsens. (In the long run, this approach can be uneconomical.)

Similar structures that could develop the same deficiency also should be evaluated for possible remedial treatment.

V. REMEDIAL ACTION: EMERGENCY AND SHORT-TERM ACTIONS

INTRODUCTION

Emergency measures . . .

- Usually must be accomplished immediately.
- Often are temporary in nature.
- Are performed primarily to prevent further damage or failure of a facility.

RESTRICT RESERVOIR ELEVATION

Restricting or lowering the reservoir reduces hydraulic pressures on dam components with structural weaknesses and allows for storage of a greater portion of the floods that would normally pass through the spillway. Reducing the frequency and size of spillway discharges reduces the risk to a spillway that has a hydraulic or structural problem.

As one example, a serious leak around the water seal of an intake structure would be a problem that may require restriction of the reservoir to avoid further damage to the structure until repairs can be made.

RESTRICT DISCHARGES

Discharges that are damaging the dam, an appurtenant structure, or the downstream channel should be restricted, if possible. Measures to restrict discharges include:

- Lowering the reservoir to allow more storage and thus reduce the discharge through the spillway or reduce the rate of discharge through an outlet works.

- Restricting the outlet works gate settings. Restricted outlet works gate settings cause more runoff to go into storage or over the spillway, which would be counterproductive if releases are being restricted to prevent downstream damage.

- During passage of a flood, temporarily closing spillway gates immediately upstream from areas where erosion damage is occurring to permit emergency repairs.

- Restricting high discharges that may be producing damage. Large fluctuations in discharges can be minimized by substituting an equivalent uniform discharge.

- During passage of a flood, delaying or regulating the release of stored flood waters so as not to increase the downstream peak discharge and associated flooding.

V. REMEDIAL ACTION: EMERGENCY AND SHORT-TERM ACTIONS

REVISE OPERATING PROCEDURES

The first and easiest step in responding to hydraulically induced damage in conveyance structures is to adopt special operational procedures for use during high flows or other emergencies that reduce the hydraulic forces on flow surfaces. These revised procedures need to be incorporated into the standing operating procedures (SOP's), and operators should be trained to apply them.

While flows are being passed, operational adjustments may limit destruction due to the following causes:

- **Erosion.** Use gated outlets, sluices, or spillway bays with the least damage.

- **Cavitation.** If possible, avoid the use of badly damaged outlet works. In pressurized conduits, the lower and most damaging pressures typically occur downstream from the regulating gates or valves at small openings. For facilities with multiple outlets, avoid these settings by using fewer outlets at full open settings, or by setting adjacent gates above or below these settings for a total equivalent discharge.

  Cavitation potential also may be limited by forcing air into the venting pipes located downstream from control valves.

- **Abrasion.** If multiple-level outlet works inlet ports are available, withdraw water from the upper level ports to avoid increased sediment concentrations at the bottom of the pool.

- **Vibrations.** Maximum vibrations normally occur at specific combinations of gate settings, reservoir elevation, and tailwater level. Identify critical zones and avoid the gate settings that fall within those zones.

- **Water hammer.** Avoid rapid changes in discharge rate in long, pressurized conduits. Water hammer problems occur most often in hydropower plants and pumping systems. The flow-regulating devices in nearly all other hydraulic facilities are designed to operate slowly enough to prevent water hammer pressure fluctuations.

V. REMEDIAL ACTION: EMERGENCY AND SHORT-TERM ACTIONS

PROTECT AND STABILIZE DAMAGED AREAS

The aprons or hydraulic jump basins of spillways normally are set at or below the downstream riverbed elevation. Hydraulic failure usually is caused by erosion of the materials downstream from and beneath the hydraulic jump stilling basin, leading to collapse of the basin.

With the basin gone, high spillway velocities may erode the foundation material and destabilize the spillway slabs. At dams where access is available during floods, emergency measures generally are limited to dumping heavy riprap or other materials into the deepest scour holes in an effort to decrease the erosion rate.

V. REMEDIAL ACTION: LONG-TERM ACTIONS

INTRODUCTION

Permanent remedial actions usually involve an engineering assessment of the problem to develop a solution. Solutions often reduce the destructive hydraulic forces as well as increase the resistance of the endangered or damaged structure to such forces.

RECONSTRUCT, MODIFY, OR STABILIZE STRUCTURES

Reconstruction, modification, or stabilization may be required for structures with:

- Hydraulic problems caused by structural movement, such as settlement, uplift, or misalignment

- Damaged flow surfaces

- Vulnerability to erosion, such as auxiliary spillway conveyance channels

There are several alternative approaches to repair or renovation. Damaged flow surfaces may be:

- Restored as closely as possible to design configuration and tolerances.

- Renovated to match original design configuration, but with superior materials that have increased resistance to applied hydraulic forces.

- Renovated with stronger materials along reshaped surfaces that are less susceptible to hydraulic forces.

The last alternative requires the most time, research, and design effort, and initially is most expensive. However, this approach probably provides the best long-term solution, particularly in locations subject to rapid surface deterioration.

Original conveyance shapes can be compared to streamlining guide references. References listed in Appendix B include:

- Hydraulic Design Criteria
- Engineering and Design, Hydraulic Design of Spillways
- Engineering and Design, Hydraulic Design of Reservoir Outlet Works
- Design of Small Dams

If damage has been severe, it is recommended that proposed shape changes be tested by modeling.

V. REMEDIAL ACTION: LONG-TERM ACTIONS

RECONSTRUCT, MODIFY, OR STABILIZE STRUCTURES (Continued)

In some cases, structures may require slight modifications to prevent damage from occurring. Examples of modifications include:

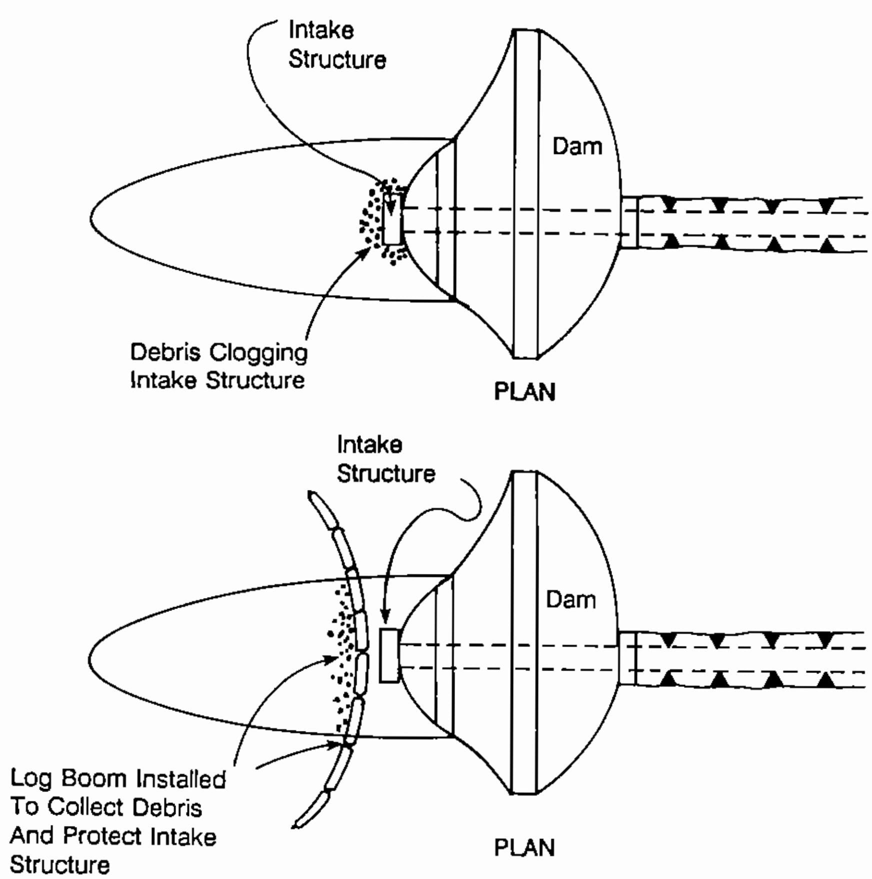
- Adding upstream guards (log booms, trashracks, screens, or other devices) to prevent debris from reaching and clogging intake structures. Trash must be removed regularly because waterlogged trash will sink and clog intakes.

- Increasing riprap size and coverage.

- Installing a concrete liner.

Figure V-1 illustrates an example of a slight modification: the addition of a log boom to protect an intake structure.

FIGURE V-1. LOG BOOM ADDED TO PROTECT INTAKE STRUCTURE



RECONSTRUCT, MODIFY, OR STABILIZE STRUCTURES (Continued)

In other cases, the most practical measure may be simply to remove the damaged structure and construct a replacement structure, if possible, including alterations that will prevent recurrence of damage. Reconstruction may be especially appropriate for external appurtenances such as intake structures, energy dissipators, trashracks, or conduits.

New structures sometimes are needed to replace outdated or poorly designed and constructed structures. Improperly functioning hydraulic jump stilling basins and plunge pools in particular are likely to require replacement with structures that incorporate current design and construction standards.

Correction Of Settlement And Movement Problems

Most structure movement problems can be related to settlement, slope failure, soil problems, foundation drain failures, or foundation solutioning. Reconstruction is necessary for correction in most instances, and should include:

- Construction keys to prevent future movement of the structure.
- Waterstops where seepage is a concern.

Refer to the TADS module Evaluation of Embankment Dam Stability and Deformation for more information about correcting settlement and movement problems.

Erosion Control

Corrective measures for controlling erosion in discharge channels of auxiliary spillways include the addition of:

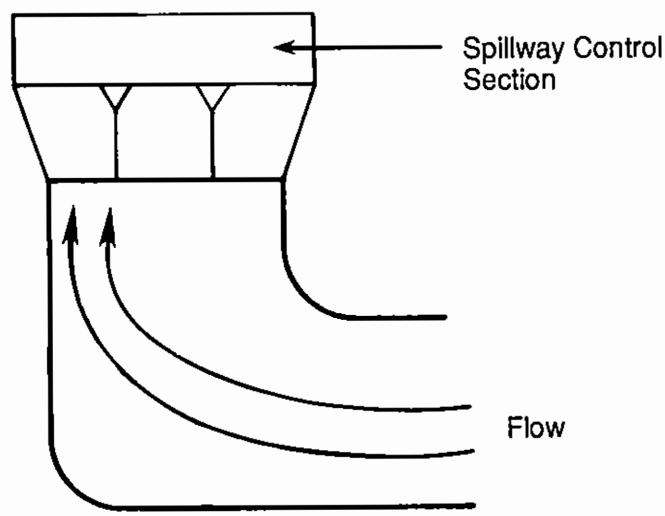
- Grade control structures, which prevent erosion from headcutting in the return channel
- Cutoff walls, which prevent undermining of hydraulic structures by streambed scour or degradation.
- Formed concrete chutes with hydraulic jump stilling basins
- Concrete or soil-cement channel liners
- Riprap
- Gabions

Erosion also may be reduced by keeping discharges uniform across the full spillway channel width. Non-streamlined approach walls typically reduce flows along the ends and concentrate flows toward one side of the spillway crest. Centerline concentrations can be reduced by streamlining the approach walls at both spillway abutments. Figure V-2 shows the effect of streamlined approach walls.

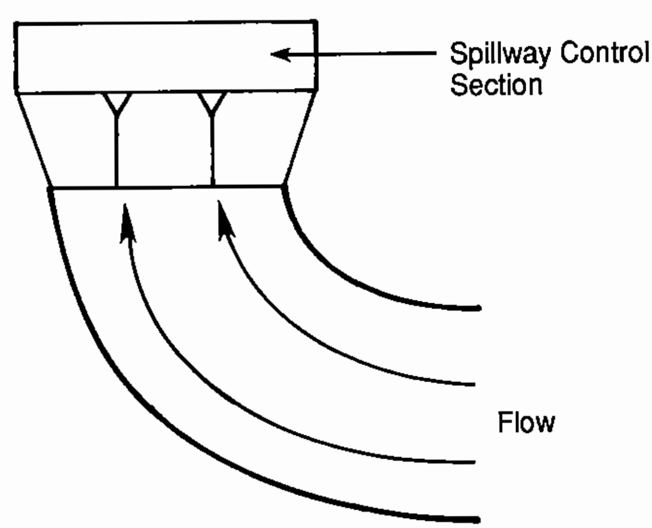
V. REMEDIAL ACTION: LONG-TERM ACTIONS

Erosion Control (Continued)

FIGURE V-2. STREAMLINING TO REDUCE FLOW CONCENTRATIONS



Nonstreamlined Approach Walls
Plan View



Streamlined Approach Walls
Plan View

V. REMEDIAL ACTION: LONG-TERM ACTIONS

Cavitation And Abrasion Erosion Control

Measures to combat cavitation damage include:

- Adding or enlarging air vents in low-pressure areas.

  The devices generally consist of an enlargement of the conduit or other conveyance structure adjacent to outlet gates or installing a slot across the floor and up each wall at chosen cross sections along the conveyance. The enlarged conduit must have sufficient air space over the flowing water to provide an uninterrupted supply to the slots from the downstream portal. Model studies are advisable to confirm proper sizing of the devices.

- Removing surface projections and irregularities.

  Surface deposits such as calcite buildup may be removed easily by chipping and scraping. Voids in the concrete surface, known as "bug holes," should be filled. Other irregularities such as form irregularities and improperly placed concrete will require surface grinding. Surface grinding should be kept to a minimum because the grinding operation often loosens or removes the larger aggregate, which could lead to future problems.

- Replacing concrete with more resistant steel plating in damage-susceptible areas.

Abrasive material may be removed from the water by using sediment pools or treating the upstream watershed, as follows:

- Raising the stilling/hydraulic jump basin end sill.

  Abrasive material eroded from downstream scour protection is pulled into the basin by the return flow eddies. These eddies occur during unbalanced spillway or powerhouse discharges. Raising the end sill prevents the material from entering the basin.

V. REMEDIAL ACTION: LONG-TERM ACTIONS

Eliminating Vibrations

To eliminate vibrations, the mass and harmonic frequencies of vibrating elements first must be determined. Changes to these values will change vibration frequency. Methods of altering vibration frequencies include:

- Changing flow characteristics by reshaping the element
- Changing the mass of the element
- Making the element less flexible

Procedures to investigate and eliminate vibrations are discussed in "Spillway Gate Vibrations on Arkansas River Dams" listed in Appendix B.

Water Hammer Prevention

Devices may be added to motors that power the opening mechanisms for automatic valves to control the maximum rate of closure or opening. Such devices gear the motors down to operate at lower rates. Surge basins or air chambers reduce the magnitude of pressure fluctuations.

PROVIDE EROSION PROTECTION

Remedial treatment for hydraulic deficiencies caused by erosion generally consists of protecting erodible material by use of various types of protective linings.

Protective linings may include:

- Vegetation
- Rock riprap
- Matting
- Concrete, roller-compacted concrete (RRC), or soil cement
- Gabions
- Geomembranes

At projects where spillway discharge channels are subjected only to minor erosion, addition of a heavy grass cover can be an effective erosion deterrent. Eroded areas within an existing vegetative cover may be backfilled, covered with topsoil, and reseeded.

The type of vegetation used depends on weather conditions, soil conditions, and flow velocities. Chapter 7 of Engineering Field Manual for Conservation Practices, listed in Appendix B, contains a description of the erosion resistance of different varieties of grasses.

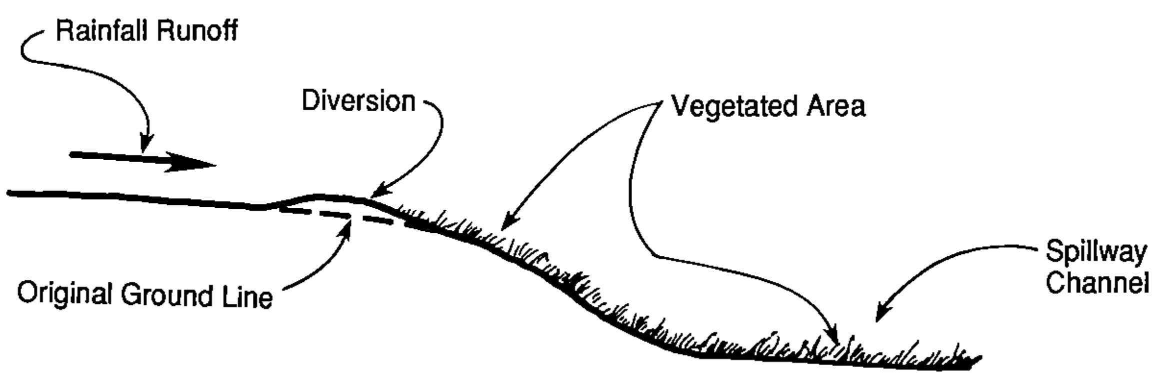
PROVIDE EROSION PROTECTION (Continued)

Matting is generally applied to minimize erosion until vegetation is established. Matting normally consists of a form of netting made of fabric, plastic, or wire, and is fastened over the eroded area to hold the soil in place until the root system of the vegetation has matured. Matting often is used on steeper slopes. Fabric netting normally is biodegradable, and decomposes within a relatively short time.

Channel side slopes may also erode from rainfall runoff. In channels where sideslopes are steep and runoff velocities are too high to maintain protective vegetation, flow interceptors or diversions (also called drainage channels or drainage ditches) frequently are provided to intercept the runoff. A diversion is a channel constructed above the slope. Figure V-3 shows a typical diversion channel above a grass-lined spillway channel.

Diversion channels are normally vegetated, or can be lined with rock or concrete if necessary to prevent erosion, particularly at the outlet.

FIGURE V-3. DIVERSION ABOVE CHANNEL SLOPE



PROVIDE EROSION PROTECTION (Continued)

Where the potential for channel erosion is more severe, other protective measures may be necessary.

- Eroded areas can be restored by filling with appropriately sized rock.

- Riprap generally is used to protect channels subject to relatively high flow velocities (up to about 12 feet per second).

- Riprap is the typical protection provided in return channels downstream from stilling/hydraulic jump basins. Examples of specific methods that have been used at existing projects to improve protection downstream from stilling/hydraulic jump basins are described in REMR Technical Note HY-N-1.3 in The REMR Notebook, listed in Appendix B.

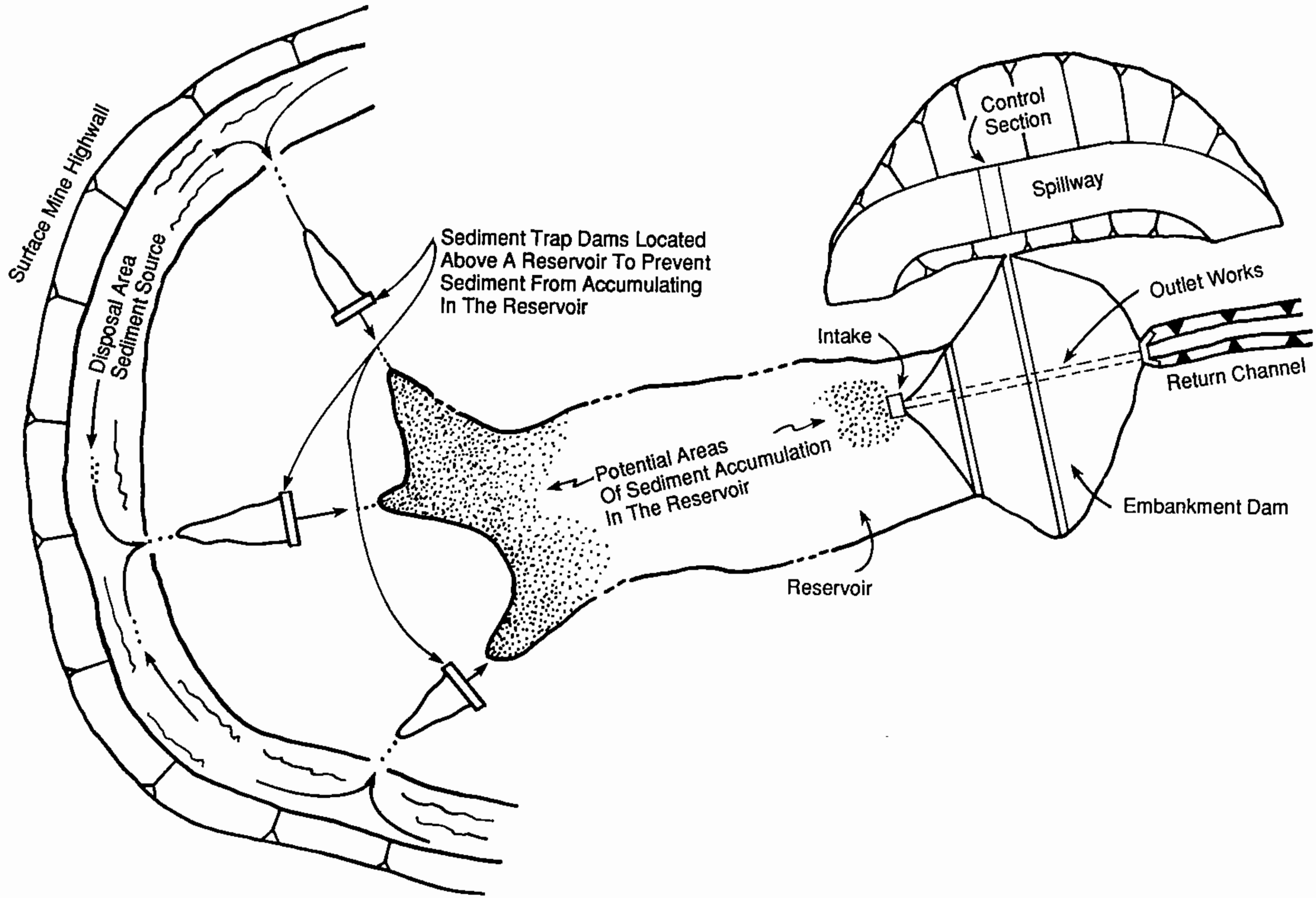
- Where extensive erosion would be expected with each discharge (for example, with flow velocities above 20 feet per second), gabion walls and mats or concrete linings may have to be used. Concrete is considered the best protection against erosion for high velocity flows (above 12 feet per second) in channels and adjacent to steep slopes.

REMOVE OR TRAP SEDIMENT

Sediment deposited in the vicinity of hydraulic structures can impede the flow of water through the structure. Sediment generally is deposited in low velocity areas or where there is a significant decrease in velocity such as the reservoir or return channels. Often the problems occur simultaneously if a serious sedimentation problem is present. Very few reservoirs can trap 100 percent of the sediment.

Often the trap efficiency decreases as the reservoir fills. Sediment is allowed to go through the outlet works conduit where it is deposited in the return channel. Removal of sediment deposits from both the reservoir and return channel will correct the immediate problem, although removing sediment from the reservoir is usually impractical. The sediment source should be stabilized to prevent a recurrence of the problem. Figure V-4 shows typical sites of sediment accumulation in a reservoir.

FIGURE V-4. SEDIMENT ACCUMULATION IN A RESERVOIR

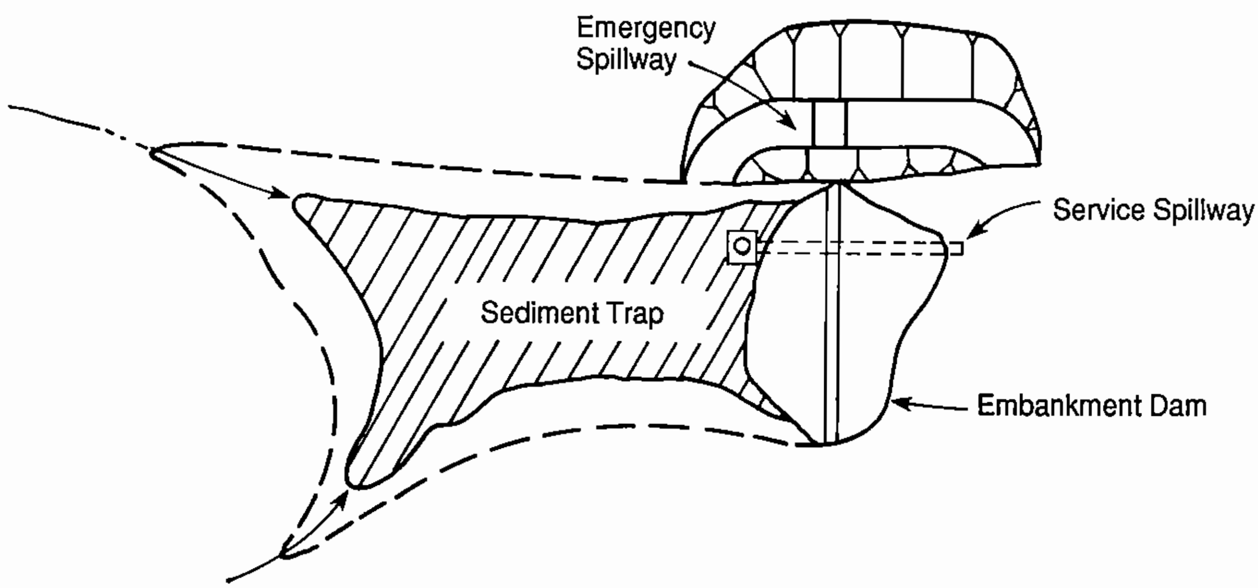


REMOVE OR TRAP SEDIMENT (Continued)

Stabilization of the sediment source may not be desirable or possible in some situations. For intakes located near the bottom of a lake, an underwater barrier placed upstream from the intake may cause the facility to draw water from the higher lake levels that usually have lesser sediment concentrations. However, such a plan should consider effects on water quality. Water from higher lake levels is generally warmer, and may have a detrimental effect on the downstream aquatic habitat.

A sediment trap placed between the sediment source and the facility to be protected prevents sediment deposition in the main reservoir and appurtenances. A sediment trap is a barrier or dam constructed across a waterway to trap sediment. These structures may be either temporary or permanent, and usually consist of a dam with a multiple port intake structure and conduit and an auxiliary spillway. Figure V-5 shows a plan view of a typical sediment trap dam.

FIGURE V-5. SEDIMENT TRAP DAM



V. REMEDIAL ACTION: LONG-TERM ACTIONS

REPAIR OR PROTECT CONCRETE

Deteriorated, damaged, or cracked hydraulic structure concrete should be repaired and protected from subsequent damage.

Concrete Repair

In general, hydraulic structures constructed of concrete that is cracked or deteriorated should be repaired before the condition worsens and eventually threatens the safety of the dam. But each situation must be evaluated individually.

The Concrete Manual listed in Appendix B contains basic information about concrete repair procedures. If the areas to be repaired are small, an injected cement or epoxy grout makes an effective repair.

Concrete Protection

Concrete subject to deterioration by acid-mine drainage or high-sulfate soils generally can be protected by applying a coating or sealant. Common sealants used include coal-tar, epoxy compounds, plastic, and rubber. Soil and water quality tests are necessary to identify the chemical nature of the problem before determining the type of sealant to use.

Concrete surfaces that are porous because of poor concrete placement or because of surface cracks are subject to water penetration. At sites subjected to frequent freeze-thaw cycles, these surfaces can experience serious surface spalling. The roughened surface from spalling can subject the surface to accelerated deterioration from hydraulic forces. Porous areas may need to be sealed to prevent water penetration.

PROVIDE CORROSION PROTECTION

Corroded metal areas should be thoroughly cleaned and then covered with protective coating. Some mechanical items require complete or partial dismantling for proper protection. Dismantling is necessary when surfaces are otherwise inaccessible for applying coatings. The disassembled parts can be coated individually and then reassembled.

If corrosive elements or chemicals have been identified in reservoir water:

- The source of the corrosive elements should be eliminated, if possible.
- Proposed repair materials should be tested for resistance to those elements.

PROVIDE CORROSION PROTECTION (Continued)

Cathodic protection should be installed for metal structures such as buried pipelines, where access to the metal surface is not practicable. Cathodic protection also may be necessary for the reinforcement in concrete structures. The two most common forms of cathodic protection protect metal structures through **sacrificial anodes** or by using **impressed current.** Refer to the TADS module Identification of Material Deficiencies for information about cathodic protection.

ADD PRESSURE RELIEF SYSTEMS

Destabilizing hydraulic pressures can be relieved by the installation of weepholes or other methods of pressure relief. A well point pumping system may be installed around the periphery of the structure to lower the ground water table and reduce uplift pressures. Pressure relief sometimes can result in settlement of the structure to its original position or at least to an acceptable position.

V. REMEDIAL ACTION: MONITORING REMEDIAL ACTIONS

INTRODUCTION

The behavior of repaired or modified structures should be monitored closely during initial operations and during different operating levels up to design loading levels.

MONITORING PROCEDURES

If remedial actions were the result of model studies, data should be collected on performance and compared with the results of the model operations. Close monitoring should continue to assure that repairs or modifications are performing as expected. Thereafter, the remedial measures should be observed regularly during scheduled inspections.

APPENDIX A

GLOSSARY

GLOSSARY

ABUTMENTS - Those portions of the valley sides which underlie and support the dam structure, and are usually also considered to include the valley sides immediately upstream and downstream from the dam.

AERATION SLOT - An air passage located on the floor of a water conveyance to equalize pressure.

AIR RELEASE VALVE - A mechanical device used to control air pressure in a conduit.

AIR SLOT - See **AERATION SLOT.**

AIR VENT - An air passage located on the roof of a conduit, usually downstream of a gate, to prevent vacuum formation and to provide ventilation.

ALKALI-AGGREGATE REACTION - A chemical reaction between certain aggregate and the alkalis (sodium and potassium, primarily in the cement) that causes irreversible expansion of concrete, and usually subsequent cracking.

ANCILLARY EQUIPMENT - Bridges, piers, decks, walkways, ladders, or other structures that provide support and access to various portions of a spillway.

APPURTENANT STRUCTURES - Auxiliary features of a dam that are necessary to the operation of the dam project. These may include spillways, outlet works, gates and valves, power plants, tunnels, and switchyards.

APRON - A section of level concrete or riprap downstream of the discharge that protects the channel or stream.

AS-BUILT DRAWINGS - Plans or drawings portraying the actual dimensions and condition of a dam and appurtenant structures as they were built. As-built drawings document construction changes to the original design due to field conditions and material availability.

AUXILIARY SPILLWAY (Emergency Spillway) - secondary spillway designed to operate only during exceptionally large floods.

BAFFLE BLOCK - A block of reinforced concrete constructed in a channel or stilling basin to dissipate the energy of the flowing water.

BALLMILLING - Repeated rotation of debris (usually rocks) that grinds a concrete surface, usually in a circular pattern.

BASCULE GATE (CREST GATE) - A spillway gate that is hinged along the bottom edge.

GLOSSARY

BLANKET DRAIN - A layer of pervious material placed to facilitate drainage of the foundation, abutment, and/or embankment.

BREACH - An eroded opening through a dam that drains the reservoir. A controlled breach is a construction opening. An uncontrolled breach is an unintentional opening that allows uncontrolled discharge from the reservoir.

CAVITATION - A process that damages concrete or metal by the formation and subsequent collapse of low-pressure bubbles in a high-velocity water flow, caused by offsets or irregularities in the flow surface.

CAVITATION DAMAGE - Damage to a concrete or metal surface caused by shock waves from the collapse of bubbles in a high-velocity water flow.

CHANNEL EROSION - The removal of channel bank and bed material by the force of flowing water.

CONDUIT - A pipe or box structure constructed by joining sections of pipe or conduit in an excavated trench, inside a tunnel, on the ground surface, or supported on cradles.

CONSTRUCTION JOINT - The interface between two successive placings of concrete where bond is intended.

CONTROL DEVICE - A gate or valve used to regulate the flow of water through an outlet works.

CONTROL GATE (OR VALVE) - A gate (or valve) that is used to regulate water flows, and therefore can be used fully open, fully closed, or at any setting in between.

CONTROL HOUSING - The structure enclosing or supporting a gate or valve that controls the release of water through an outlet works.

CONTROL SECTION - A spillway component that receives the flow of water from the entrance channel and determines the elevation and capacity of the flow.

COUPONS - Rectangular samples of metal.

CREST - The top surface of the dam or high point of the spillway control section.

CUTOFF COLLAR (SEEPAGE COLLAR) - Projections around a conduit within the impervious portion of a dam to lengthen the seepage path along the outer surface of the conduit.

GLOSSARY

CUTOFF WALL - A wall of impervious material, usually concrete, soil-cement, cement-bentonite, asphaltic concrete, or steel sheet piling, constructed under or through a dam or a structure to halt seepage through, beneath, or adjacent to the dam.

DEAD STORAGE - The portion of the reservoir located below the sill of the lowest outlet works gate, or other opening, which cannot be drained. This reservoir space is usually reserved for sediment storage.

DEFICIENCY - An anomaly or condition that affects or interferes with the proper and safe operation of the dam.

DESICCATION - The process of drying-up or dehydrating.

DIFFERENTIAL MOVEMENT - Localized movement of one section of a structure relative to adjacent sections.

DISCHARGE CHANNEL (CHUTE) - An open channel that conveys spillway flow from the control section to the energy dissipation section, return channel, or natural stream.

DISCHARGE SECTION - A spillway component that conveys flow from the control section to the terminal section, return channel, or stream.

DOLOS - Fabricated concrete wave dissipating structures, usually placed over riprap.

DOWNSTREAM CHANNEL (RETURN CHANNEL) - The waterway downstream from the dam, where water is returned to the original river or stream after having its excess energy dissipated.

DOWNSTREAM FACE - The inclined surface of a concrete dam that faces away from the reservoir.

DOWNSTREAM SLOPE - The inclined surface of an embankment dam that faces downstream, away from the reservoir.

EMBANKMENT - Fill material, usually earth or rock, placed with sloping sides.

EMBANKMENT DAM - Any dam constructed of excavated natural materials (includes both earthfill and rockfill dams).

ENERGY DISSIPATOR (TERMINAL STRUCTURE) - An appurtenance at the end of spillways and outlet works that uses turbulence to aid in the dispersal of excess energy in the water. Types include baffles, plunge pools, impact basins, stilling pools, and stilling wells, among others.

GLOSSARY

ENTRANCE CHANNEL - A structure that conveys water to the control section of the spillway or to the intake structure of the outlet works.

EROSION - The wearing away of the land surface by detachment and transport of soil and rock material through the action of moving water.

FLASHBOARDS - Individual boards or panels supported by vertical pins or stanchions anchored to the spillway crest to increase storage.

FLIP BUCKET - An upward-curved structure located at the end of a chute, designed to be used when water depth does not permit a hydraulic jump to form.

FREEBOARD - The vertical distance between a stated water level and the top of a dam or spillway crest.

FREE FLOW (OPEN-CHANNEL FLOW) - Flow that occurs either in an open waterway or in a conduit that flows partly full.

FULL CONDUIT FLOW - See **PRESSURE FLOW.**

GABION - A prefabricated, square, or rectangular wire cage or basket filled with rocks. Gabions are free-draining and capable of being stacked for slope protection.

GATE - An adjustable device used to control or stop the flow of water in a waterway. A gate consists of a leaf or member which is moved across the waterway from an external position.

GROIN (SLOPE-ABUTMENT INTERFACE) - The contact between the abutment and the embankment slopes.

HEADCUTTING - Erosion of earthen materials that progresses upstream.

HYDRAULIC JUMP - The abrupt rise in water surface that may occur in an open channel or stilling basin when water flowing at high velocity is suddenly slowed down.

HYDRAULIC JUMP BASIN - See **HYDRAULIC JUMP STILLING BASIN.**

HYDRAULIC JUMP STILLING BASIN (STILLING BASIN, JUMP BASIN) - A structure designed to produce a hydraulic jump that will dissipate energy.

HYDROGRAPHIC SURVEY - The depiction of the relief of the earth's surface including natural and manmade features in underwater areas by use of positioning and sounding equipment or other land surveying methods.

GLOSSARY

INACTIVE STORAGE - Storage area that accommodates sediment deposition, fish and wildlife conservation, and recreational purposes. Water in this area is only withdrawn from the reservoir during an emergency.

INTAKE STRUCTURE - Placed at the beginning of an outlet works waterway, the intake structure establishes the ultimate drawdown level of the reservoir by the position of its opening(s) to the outlet works. Intake structures may be vertical or inclined towers, drop inlets, or submerged, box-shaped structures. Intake elevations are determined by the head needed for discharge capacity, storage reservation to allow for siltation, the required amount and rate of withdrawal, and the desired extreme drawdown level.

JUMP BASIN - See **HYDRAULIC JUMP STILLING BASIN.**

LEAKAGE - The undesirable flow of water through joints, cracks, and openings in hydraulic structures.

MISALIGNMENT - The movement of a structure from its design location.

OGEE - A weir profile shaped with a curving crest and downstream face.

> **Ogee Crest** - An ogee used as a control in combination with other spillway elements.
>
> **Ogee Spillway** - A drop spillway constructed in the ogee form.

OPEN-CHANNEL FLOW - See **FREE FLOW.**

OPERATING BRIDGE - A structure that extends over the control section to support gates and other equipment.

ORIFICE - The opening of an inlet structure, or the open end of a conduit or tunnel.

OUTFALL - The outlet end of a toe drain, or the point where the constructed return channel meets the natural stream.

OUTLET WORKS - A system of dam components that regulates or releases water impounded by a dam. Components of an outlet works include an entrance channel, intake structure, conduit, gate or valve housing, energy dissipators, and return channel.

OVERFLOW CREST - A weir or sill designed for water to spill over when the reservoir level rises above the weir elevation.

GLOSSARY

SHOTCRETE - A sand, cement, and water mixture sprayed on rock, concrete, or compacted earth.

SINKHOLE - A depression resulting from loss of material underlying the surface.

SLIDE - The unplanned descent of a mass of earth or rock down a slope.

SLOPE-ABUTMENT INTERFACE - The contact between the abutment and embankment slopes.

SLUICE - A low-level opening for releasing water from a dam.

SOIL-CEMENT - A well-compacted mixture of soil, Portland cement, and water that produces a hard material similar to concrete.

SPALLING - The loss of chunks of concrete from a surface, usually because of compression, impact, or abrasion.

SPILLWAY - A structure over or through which flows are discharged. If the flow is controlled by mechanical means, such as gates, it is considered a controlled spillway. If the elevation of the spillway crest is the only control, it is considered an uncontrolled spillway.

STANDING OPERATING PROCEDURES (SOP) - Written guidelines to be followed for normal and emergency operation of the components of a dam.

STILLING BASIN (HYDRAULIC JUMP STILLING BASIN, HYDRAULIC JUMP BASIN) - A structure designed to produce a hydraulic jump that will dissipate energy.

STOPLOGS - Large logs, timbers, or steel beams placed on top of each other with their ends held in guides on each side of a channel or conduit to provide an inexpensive and easy means of closure.

SULFATE ATTACK - Chemical and/or physical reaction between sulfates (usually in soil or ground water) and concrete or mortar. Deterioration of the concrete or mortar may result. Sulfate attack is common in older dams in the western United States where sulfate-resistant cement was not used, or alkali aggregate was used.

TAILRACE - A powerhouse return channel.

TAILWATER - Water at the toe of a spillway or outlet works, such as water in a stilling basin, plunge pool, or stream. The water downstream from a structure or dam.

GLOSSARY

TERMINAL SECTION - A structure containing one or more energy dissipators.

TERMINAL STRUCTURE - See **ENERGY DISSIPATOR.**

TOE OF DAM - The junction of the downstream slope of a dam with the ground surface; also referred to as the **downstream toe.** For an embankment dam, the junction of the upstream face with the ground surface is called the **upstream toe.**

TRAINING DIKE OR WALL - A dike or wall that trains or directs flow to a desired location while protecting the surrounding area or nearby embankment.

TRASH BOOM - A floating structure that provides a barrier to catch debris and prevent it from entering a spillway.

TRIBARS - Fabricated concrete wave dissipating structures formed by interconnecting three vertical columns, usually placed over riprap.

TRIPOD - A fabricated concrete wave dissipating structure in a tetrahedron shape, usually placed over riprap.

TUNNEL - An enclosed waterway excavated through in situ material, usually away from the dam.

UPSTREAM FACE - The inclined surface of a concrete dam that is in contact with the reservoir.

UPSTREAM SLOPE - The inclined surface of an embankment dam that is in contact with the reservoir.

VALVE - An adjustable device used to control or stop the flow of water in a waterway. A valve is fixed permanently within the waterway, and has a closure member that is either rotated or moved transversely or longitudinally in the waterway in order to control or stop the flow.

WATER CONVEYANCE COMPONENT - A channel, tunnel, or conduit of a spillway or outlet works.

WATER CONVEYANCE STRUCTURE - A non-specific reference to a spillway, a conduit, or tunnel, an outlet works, an open channel, or a penstock.

WATERSTOP - A continuous strip of waterproof material, usually PVC, metal, or rubber, designed to control cracking and limit moisture penetration through concrete joints.

WATERWAY - An open channel, conduit, or tunnel that conveys water.

GLOSSARY

WEATHERING - Changes in color, texture, strength, chemical composition, or other properties of a natural or artificial material due to the action of the weather.

WEEPHOLE - A drain embedded in a concrete or masonry structure to pass moisture from behind or below the structure to relieve pressure.

WEIR - A structure of given shape and dimensions built across a stream or channel to control or measure flow quantities.

APPENDIX B

REFERENCES

REFERENCES

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APPENDIX C

RESEARCH FACILITIES AND SOURCES OF ASSISTANCE

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AGENCIES PERFORMING ANALYTICAL HYDRAULIC STUDIES

Many Federal and State agencies that are involved with building and operating dams have engineering departments that conduct hydraulic analyses as well as other dam design studies. Federal agencies include the Bureau of Reclamation, the Corps of Engineers, the Tennessee Valley Authority, the Soil Conservation Service, and the Department of Agriculture.

The water resource departments of many State governments also have engineering units capable of conducting hydraulic analyses.

In addition, many civil engineering firms regularly conduct hydraulic design studies not only for private companies but also for government agencies. A civil engineering firm that performs analytical hydraulic studies should have recent experience in dam design or modification work to ensure acceptable quality.

LABORATORIES PERFORMING HYDRAULIC STUDIES

Laboratories with modeling and research facilities are:

- Corps of Engineers Waterways Experiment Station
  Vicksburg, Mississippi

- Norris Engineering Laboratory
  Norris, Tennessee

- USDA Agricultural Research Service
  Plant Science and Water Conservation Laboratory
  Stillwater, Oklahoma

- Saint Anthony Falls Hydraulic Laboratory
  Saint Anthony Falls, Minnesota

- U.S. Bureau of Reclamation
  Research and Laboratory Services Division
  Denver, Colorado

RESEARCH FACILITIES AND SOURCES OF ASSISTANCE

LABORATORIES PERFORMING HYDRAULIC STUDIES (Continued)

- Alden Research Laboratory, Inc.
  Holden, Massachusetts

- National Water Research Institute
  Hydraulic Laboratory
  Burlington, Ontario

- Corps of Engineers Cold Region Research and Engineering Laboratory
  Hanover, New Hampshire

Various colleges and many State universities have hydraulic laboratories and do testing for outside agencies. Among those specifically directed toward hydraulic research are:

- Colorado State University
  Fort Collins, Colorado

- Iowa Institute of Hydraulic Research
  University of Iowa
  Iowa City, Iowa

- Villanova University
  Philadelphia, Pennsylvania

A number of private hydraulic laboratories also may be able to offer assistance. Many hydraulic features can be investigated through multidimensional mathematical models. The Hydrologic Engineering Center in Davis, California is a U.S. Government facility providing this service. Laboratories at many universities also perform mathematical modeling.

SOURCES FOR PUBLISHED HYDRAULIC RESEARCH

Organizations that publish research results and maintain technical libraries on hydraulic topics include most of those listed previously.

In addition, the Army Corps of Engineers' Repair, Evaluation, Maintenance, and Rehabilitation Research Program (REMR) issues the following publications:

- <u>The REMR Bulletin</u>
- <u>The REMR Notebook</u>
- Technical Reports

RESEARCH FACILITIES AND SOURCES OF ASSISTANCE

SOURCES FOR PUBLISHED HYDRAULIC RESEARCH (Continued)

The REMR program includes a hydraulics-specific work area that performs unique investigation of maintenance and rehabilitation issues.

Another source for published hydraulic research is:

Electrical Power Research Institute
Reports Research Center
P.O. Box 50490
Palo Alto, California 94303