EXISITING FACILITY INTEGRITY

VOLUME IV

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SECTION 1
INTRODUCTION AND OVERVIEW

Scope

This volume presents guidelines for investigating and evaluating, at the feasibility level, existing dams and appurtenant structures to determine their structural suitability for the addition of small hydroelectric facilities. These guidelines are applicable for dams of heights up to about 100 feet. The more common modern and older types of dams are covered herein, since they are the most likely to be considered for the addition of small hydroelectric facilities. For dam types not covered herein, the principles discussed should provide sufficient guidance for their investigation.

For the purposes of this report, dams are classified into the following four basic categories:

1. Earth and rockfill
2. Concrete
3. Masonry
4. Miscellaneous (includes stonewall-earth and rockfill timber crib).

Appurtenant works included in this document are those that exist prior to the addition of new hydroelectric facilities; they consist of spillways and outlet works for the most part, though occasionally they may include existing penstocks, powerhouses, and flumes.

Section 2 presents a classification and description of the types of dams and appurtenant works that are expected to be encountered most often during investigations for the addition of small hydroelectric facilities. Also included in Section 2 are detailed discussions of reservoir conditions from an integrity viewpoint, common deficiencies and failure modes of dams and appurtenant works, and the adverse effects that power additions may have.

Section 3 presents recommended methodology, guidelines, and personnel requirements for performing the investigations.

Section 4 discusses methods of rehabilitating the various components of existing facilities if found to be deficient.

Section 5 presents guidelines for estimating the costs for performing the various stages of the integrity investigations and for performing rehabilitation works. It must be pointed out that dams are unique structures, each fitting specific site and material conditions; that costs will therefore vary widely depending on site-specific conditions; and that considerable judgment is required for estimating realistic costs for both engineering and rehabilitation work.

Objectives of Integrity Investigations

The installation of hydroelectric facilities at existing dams will require significant capital investments, and there are liabilities to consider should the dam fail and cause loss of life and destruction of property downstream. It is therefore prudent to determine if the existing facilities are structurally sound and will perform adequately if modified and operated as a hydroelectric facility prior to committing the necessary investment for modifications. Studies of failure probability at any time during the life of a dam indicate that, where failures occur, the incidences of failure during initial years of operation are relatively high; thereafter the probability of failure at any time decreases for a number of years, and then increases rather dramatically as the dam deteriorates after many years of existence. Thus, the fact that a dam has performed adequately for a number of years is not proof that it is structurally sound. In fact, the opposite may be true: it may have deteriorated to the point that it is about to experience difficulties and may even fail.

The integrity studies discussed herein serve a different purpose than do surveillance and inspections of dams conducted by local, state, and federal regulatory agencies, which are concerned with the safety and protection of downstream inhabitants and property. The prior determination by an agency that a dam has been safe under existing operating conditions, while indicating that it is more likely to be sound than a dam not so studied, does not assure that the facility will continue to be sound under hydroelectric operating conditions, or that excessive maintenance will not be required for the life of the project. Several types of dams, such as some in the New England area, that are likely to be considered for installation of hydroelectric facilities do not meet the legal definition of a dam accepted by dam safety regulatory agencies, and they have not been evaluated for safety by appropriate governmental agencies.

The primary objectives of the type of integrity investigation discussed herein are to determine the structural integrity of existing facilities for hydroelectric power operational conditions, to evaluate the cost of remedial work, if required, and to assess maintenance requirements and the expected longevity of the existing facilities.

Major Technical Components of a Feasibility Level Investigation

From technical, cost effective, and administrative viewpoints, the integrity investigations of existing facilities to determine the feasibility of adding hydroelectric power units may be best accomplished by a program that has potentially one to three stages:

Stage 1 - Evaluation of existing data and site inspection
Stage 2 - Developing new data and performing additional evaluations
Stage 3 - Developing designs for rehabilitation and construction cost estimates.

The Stage 1 investigation consists of collecting, reviewing, and evaluating available data and information pertaining to the facilities; making a detailed site inspection; evaluating the existing facilities for the intended use; and making recommendations for additional investigations, if appropriate. If the dam and facilities are relatively new and if sufficient data are available, it may be possible to determine that no additional investigations are required and that the dam and facilities are adequate for the addition of hydroelectric facilities. If the dam is old, and/or adequate data are not available, or the site inspection reveals the possibility of potential problems, a Stage 2 investigation will be required. The final step of the Stage 1 investigation is preparation of a report which presents the evaluation of the existing facilities and recommendations as to any problems related to adding power facilities; the report would also include a program and cost estimate for a second-stage investigation, if required.

Stage 2 consists of implementing the program of additional investigations developed during Stage 1 if the dam is not deemed suitable for direct hydro addition. This consists of developing additional required data by drilling, sampling, and testing; evaluating the new data; analyzing portions of the facilities that are questionable; and preparing a report that describes the work that was performed and presents the data developed, results of analyses, evaluation of the facilities, recommendations, and a Stage 3 program, if recommended. The Stage 2 program must be kept flexible and the investigation modified to accommodate or evaluate unanticipated conditions that are revealed during the investigation, so that the required data are obtained and the work is cost effective. If the Stage 2 investigation indicates that the dam and facilities are suitable for the addition of hydroelectric facilities, Stage 3 would not be required. If rehabilitation of the dam and/or facilities is required, a program for Stage 3 would be developed.

Stage 3 consists of developing methods of rehabilitating the dam and/ or facilities and estimating the cost of construction to make the dam and facilities suitable for adding hydroelectric facilities.

If, at any time during the various stages of investigation, it becomes obvious that the existing facilities are technically unsuitable or that rehabilitation costs will be excessive, the investigations should be terminated. In addition, if significant integrity problems exist at a dam, the dam owner or operator should be notified so that the deficiencies can be examined further and corrected so as to minimize hazard to life and property.

Intended Use of These Guidelines

This volume, as well as the other volumes of the manual, is intended for the use of owners of potential power sites, governmental agencies, private consultants, and research and educational institutions. The use of this volume by non-technical individuals (i.e., persons other than engineers and geologists) should be limited to selecting people competent to perform the work, planning for investigation costs, and administering theinvestigation program. The investigation of existing structures to determine the feasibility of utilizing them for the addition of hydroelectric facilities must be performed by engineers and engineering geologists with experience related to dams and other hydraulic structures.

The addition of hydroelectric facilities represents a significant financial investment and, as attested by past dam failures, human lives and property downstream of a dam can be in jeopardy. Since the dam is the focus of and essential to the project, it is imperative that the suitability of the existing facilities be firmly established before capital is committed to the addition of hydroelectric facilities and the liability for the consequences of a dam failure is assumed. Dams and appurtenant structures are complex, and knowledge covering a wide range of geology, hydrology and various applicable engineering fields is required to adequately evaluate existing dams. It is beyond the scope of this volume to provide basic engineering and geologic information to technically educate all readers. It is therefore presumed that persons utilizing this volume for evaluating the technical suitability of existing dams and appurtenant structures have a basic understanding of geology, soils engineering, structural engineering, hydrology, and hydraulics, with sufficient experience to apply engineering judgment during the feasibility evaluations.

This volume can be best utilized to obtain an awareness of the more common problems that have been historically associated with dams and that the investigator must be alert for; and beyond that, the volume provides a means of organizing and performing the investigation, and offers guides to methods of rehabilitation and cost estimating. This volume cannot be used as a substitute for proper educational background, experience and engineering judgment, which are essential to the proper conduct of this type of investigation. A recognized expert in any areas of concern should be consulted before a project is adopted as feasible.

SECTION 2
CLASSIFICATION OF DAMS
AND PRINCIPAL AREAS OF CONCERN

Classification and Description of Principal Dam Types

Dams are generally classified on the basis of materials used for their construction. The basic dam classifications are (1) concrete, (2) masonry, (3) earth and rockfill, with the remainder grouped as (4) miscellaneous. These basic categories can be further subdivided based on geometric configuration or internal zoning. Composite dams consist of a combination of two or more different types of structures.

Concrete Dams. Concrete dams include gravity, arch and buttress types. Examples are shown in Figures 2-1 through 2-4. Concrete gravity dams depend on their mass for stability, and may be either straight or (sometimes) curved in plan. The curved plan takes advantage of the arch action for added strength. Gravity dams generally require sound rock foundations but may be founded on alluvial foundations. Concrete gravity sections are often used as overflow sections for composite dams. Concrete gravity dams founded on pervious foundations require special design considerations to control seepage, prevent excessive uplift pressures, and maintain the integrity of the foundation.

Concrete arch dams utilize arch action to transmit most of the water load from the reservoir to the dam foundation and/or abutments. In order to transmit the arch action to the abutment walls, the arch dam must act as a monolithic structure and thus be free of open cracks and other structural discontinuities. Arch dams are much thinner in section than gravity dams. The U.S. Bureau of Reclamation classifies arch dams with a b/h ratio (ratio of the base thickness of the crown cantilever to the structural height of the dam) of 0.2 and less as thin, between 0.2 and 0.3 as medium thick, and 0.3 and greater as thick. Arch dams may be either single or double curvature and the radius of curvature may be constant or variable.

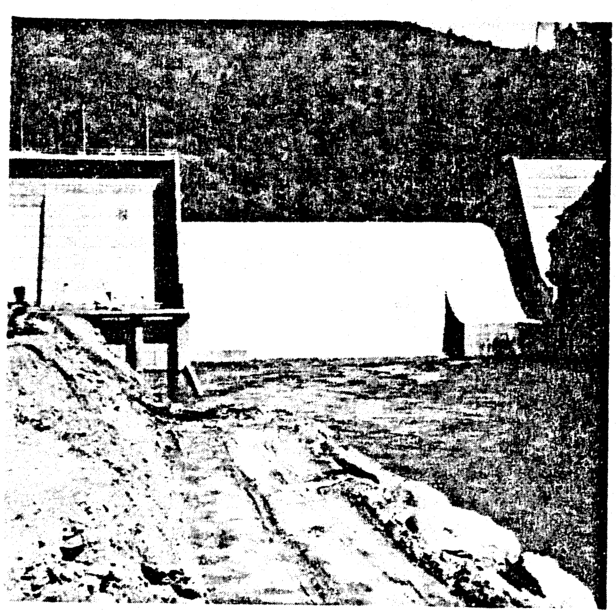

Figure 2-1. Concrete gravity dam.

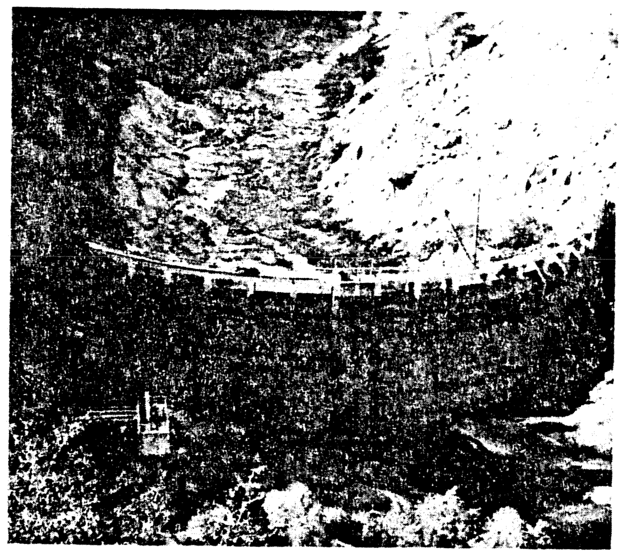

Figure 2-2. Variable radius arch dam with radial spillway gates, control for low level river outlet, and intake structure for tunnel outlet

Since the majority of the reservoir force is transmitted to the abutments of an arch dam, the abutments must be capable of withstanding the arch thrust. Narrow canyons with steep, strong walls are generally best suited for arch dams.

Buttress dams utilize a sloping membrane, generally of concrete, to transmit hydrostatic forces to a series of structural buttresses placed at right angles to the dam axis. There are several types of buttress dams, including flat-slab or Ambersen, multiple arch, multiple dome, roundhead, diamondhead, and cantilever buttresses. The most common and important buttress dams are the flat-slab and multiple arch. A few timber and steel deck buttress dams have been constructed. Buttress dams generally require considerably less concrete than gravity dams of the same size, but require more formwork. Reinforcement is required in buttress dams with thin slabs or arches.

Buttress dams are best suited to wide valleys with gradually sloping abutments; they can be founded on rock or sound alluvium. Depending on the foundation, the buttress may be cast directly into excavation into rock or supported by spread footings, or a continuous slab foundation may be utilized for alluvial foundations. Flexible joints are normally provided between adjacent slabs and buttresses, allowing each section to act independently. Thus, minor settlements and deformations are not critical.

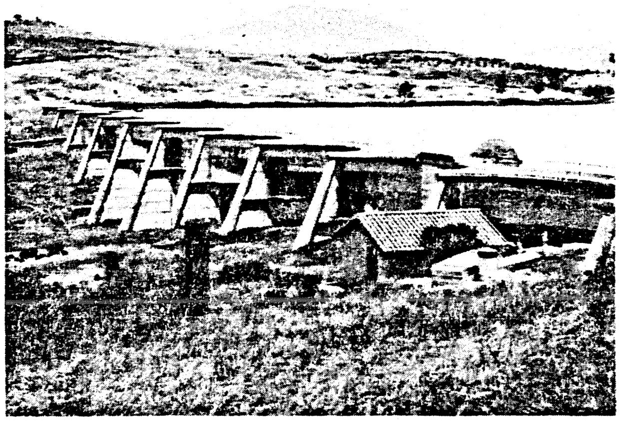

Figure 2-3. Multiple arch dam.

Masonry Dams. Masonry dams consist of rubble or stone laid in mortar (Figure 2-5). Both gravity and arch masonry dams have been constructed. These are similar in section and foundation requirements to concrete dams. Masonry dams were a principal type of dam constructed before rising labor costs and better utilization of mass concrete made them uneconomical. Most masonry dams were constructed before the twentieth century and there have been few, if any, significant masonry dams constructed in the United States for several decades.

Earth and Rockfill Dams. Earth and rockfill dams utilize natural materials for construction. The development of large, rapid performing, earth-moving equipment in recent years has made these types of dams extremely cost competitive. In addition, earth dams can be constructed on foundations that are unsuitable for other types of dams. Examples of earth dams are shown on Figures 2-6 through 2-8.

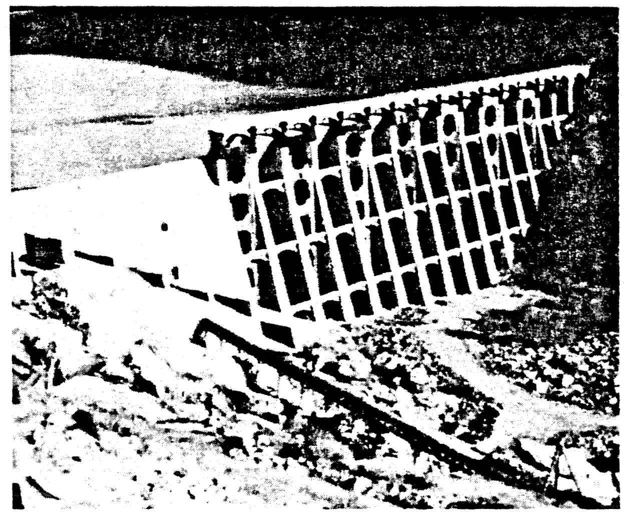

Figure 2-4. Multiple arch dam (buttresses have been strengthened and cross channel stability increased by added diaphragm)

In the past earth dams were constructed by loose fill and hydraulic or semi-hydraulic methods. The rolled fill (or compacted fill) type of construction is now used almost exclusively. There are several types of earth dams, including homogeneous, zoned, and diaphragm types.

Homogeneous dams are constructed of essentially one type of material. In order to control the level of saturation and water pressure within embankments,

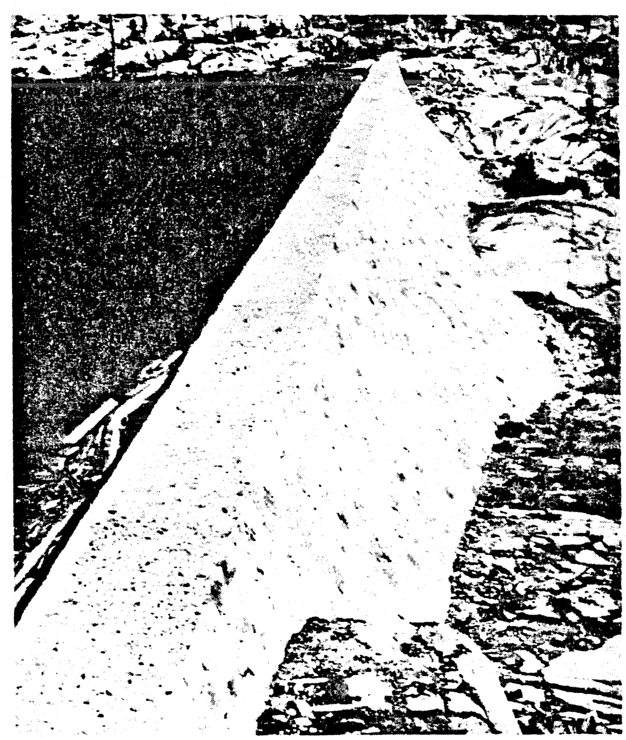

Figure 2-5. Gunite-faced masonry dam

drainage zones are often used. Homogeneous dams modified in this way can have either rockfill toe drains, blanket drains, chimney drains or combinations of these drains. These drain zones are constructed of essentially freedraining sand or gravel, protected with suitable filter zones to prevent migration of fine-grained soils into the coarser drain zones.

Zoned earth dams consist of an impervious zone surrounded by more pervious shells. The shells generally consist of sand, gravel, or cobbles; they support the dam core and increase dam stability by controlling the phreatic surface within the embankment. Piping of the fine-grained core material into the coarser shells is prevented with selected graded filter zones. The dam core can be either central or sloping upstream.

Figure 2-6. Zoned earth dam under construction

Diaphragm type earth dams consist of pervious material (sand or gravel) with a thin impervious membrane or diaphragm which acts as an impermeable barrier. The diaphragm may be centrally located or may form the upstream face of the dam. Earth, cement concrete, and asphaltic concrete, asphaltic membranes, and plastic and rubber sheets have been used as diaphragm material.

Rockfill dams are constructed of rock with an impervious membrane. The rockfill provides stability while the impervious membrane serves to retain the water. The impervious membrane is protected by filter or bedding zones and transition zones. The membrane may be an upstream facing or a thin interior core. The upstream

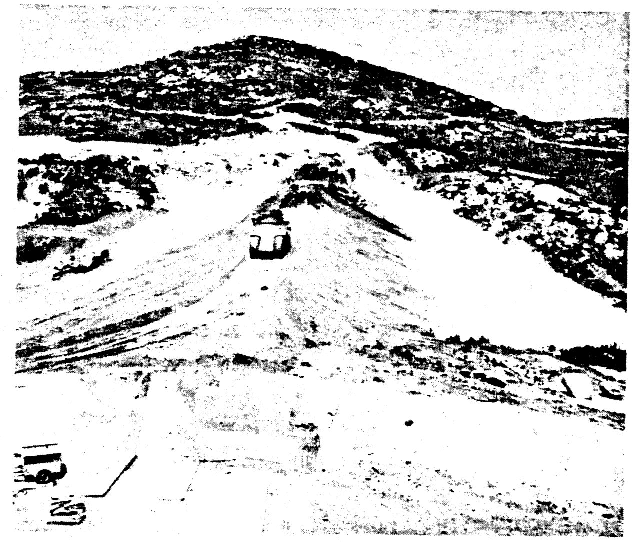

Figure 2-7. Constructing crest of earth dam (spillway control structure in foreground)

facings of rockfill dams have been constructed of impervious soil, concrete slabs, asphaltic concrete and steel plates. Interior cores are generally of earth. The rockfill sections have been constructed with dumped rock (sluiced or dry) and by placing and compacting the rock in horizontal lifts. Rockfill dams usually require either a rock or a competent sand or gravel foundation.

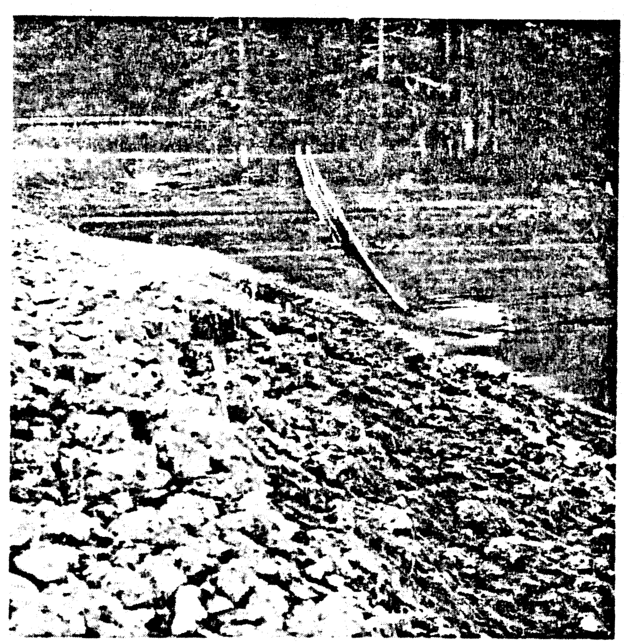

Figure 2-8. Earth dam (line of stakes marks failure scarp)

Miscellaneous Dams. The more important dams in the miscellaneous category include timber dams (Figure 2-9) and stonewall-earth dams (Figure 2-10). A number of small timber dams have been constructed in the west and northwest. Most timber dams are less than 20 feet high, but a few have been constructed that are over 60 feet in height. These dams have a relatively short life due to rotting of the timbers. However, with maintenance, these dams have performed successfully for a number of years. There are several types of timber dams. These include rockfilled crib, frame and deck, crib and deck, and beaver type. Other than the rockfilled crib dams, most of these dam types are rarely over 10 feet in height.

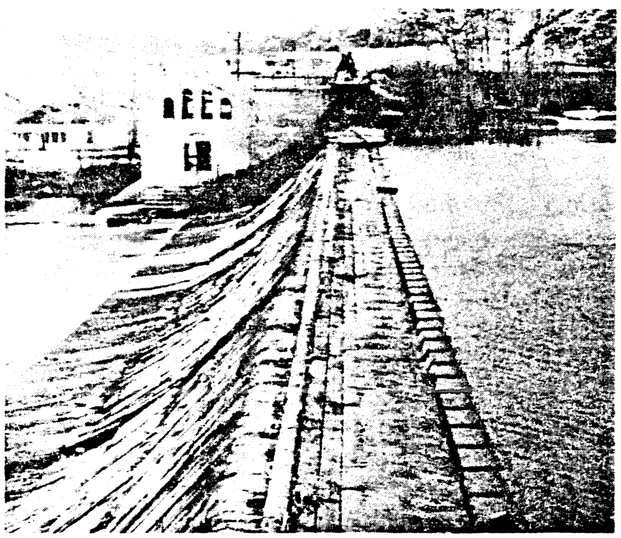

Figure 2-9. Timber crib dam

There are at least several hundred stonewall-earth dams located in the northeastern U.S. These dams generally consist of an upstream earth section with a downstream vertical to near-vertical wall of stacked stone. Mortar has generally not been used in the stonewall. These dams are generally less than 30 feet high with most of the dams under 10 feet high. Most are 100 to 200 years old.

Beyond these discernible categories, there are structures which combine various design principles and construction materials. One example is shown in Figure 2-11.

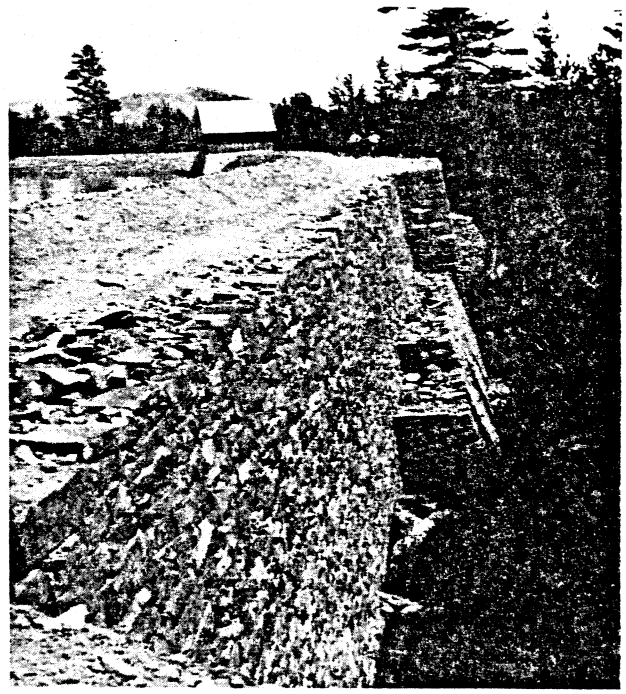

Figure 2-10. Stonewall-earth dam

The Reservoir

There are primarily two types of reservoirs where hydroelectric facilities may be installed at existing impoundments. One is a run-of-the-river type installation where the heads are low and reservoir capacity

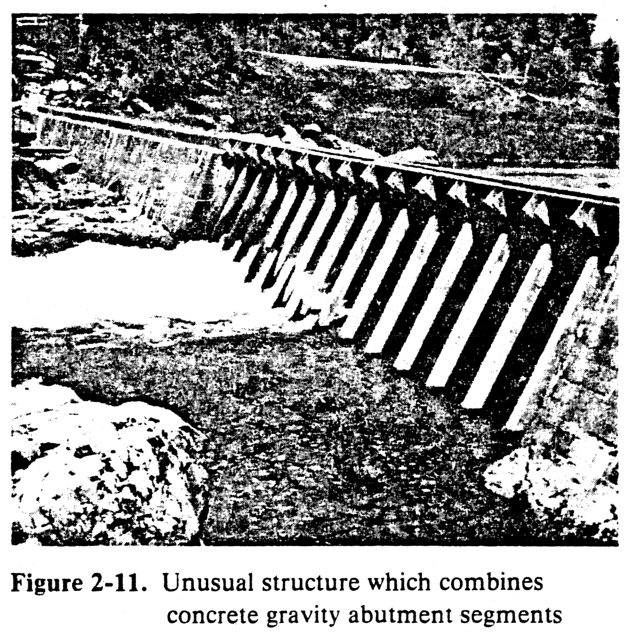

Figure 2-11. Unusual structure which combines concrete gravity abutment segments with central timber slab and buttress segment

small, and where there would not be much fluctuation in the reservoir level. The other type of facility consists of a storage reservoir where the reservoir level will fluctuate significantly.

For the run-of-the-river type installation, reservoir conditions would not vary significantly from existing conditions and therefore the addition of hydroelectric facilities would not have a significant effect on the reservoir. Past performances of these types of reservoir would offer an excellent guide to the reservoir conditions that would be expected after the hydroelectric facilities were added.

At the storage type of reservoir, the installation of hydroelectric facilities may not change the reservoir operating conditions significantly, or it could result in major changes in the operation of the reservoir. If hydroelectric power is generated from normal releases of water (such as for irrigation purposes), then reservoir operating conditions would not change significantly and past performance would fairly indicate the reservoir conditions that would be expected after the hydroelectric facilities were added. If the reservoir had been performing well for a number of years, the investigation would be directed primarily towards signs of progressive deterioration.

If the reservoir had been operating at a relatively constant level (such as essentially full, as for a recreation facility), and if power releases resulted in a significant reduction in the reservoir level, some of the previous benefits could be impaired and the change in operating conditions could significantly affect the performance of the reservoir. Drawdown conditions have long been recognized by earth dam designers as one of the most critical conditions affecting stability of the upstream slope of a dam. Reservoir drawdown conditions could also create adverse slope stability conditions in the reservoir just as in an earth dam. Therefore, if a reservoir has not been subjected to drawdown, past performance is not an adequate guide for this operating condition. In this case, the potential for dam slope and reservoir side slope slides would have to be investigated to evaluate the possibility of impairing the functioning of the dam, appurtenant structures, and reservoir; endangering facilities above the reservoir level; or, if no facilities are involved, of producing scars along the reservoir rim that are not acceptable.

If storage in the reservoir is increased beyond previous operating levels (as for a flood storage facility), the benefits could also be impaired and the performance of the reservoir could be significantly different. Reservoir slope stability could be reduced because of additional saturation and drawdown; and reservoir seepage could be a problem because the upper level of the reservoir might not be as impervious as the lower levels.

Appurtenant Works

The appurtenant works are the structural facilities associated with a dam by means of which the purposes of the dam and reservoir and the use of the water are achieved, usually by controlling the flows of water which enter and leave the reservoir. The most common and critical appurtenances are spillways and outlet works. If power plant components are closely integrated with a dam, hydraulically or structurally, the plant can be considered an appurtenance. Navigational locks, fish ladders, and log sluices are other kinds of appurtenances. Inlets also are associated with dams which store water from a remote source.

Spillways. Spillways are required at storage dams for releasing incoming flood waters that are in excess of available reservoir capacity. They are also required at diversion dams to bypass stream flows in excess of the diversion capacity.

Separately identifiable spillway components are the approach or entrance channel, the control structure, the discharge channel, the terminal structure, and the return or outlet channel. Some examples are shown on Figures 2-12 and 2-13. The topography, geology, dam type and spillway type determine which components are needed.

The entrance channel conveys water from the reservoir to the control structure and is usually required except for concrete dam overflow spillways. The channel profile and cross sections are sized and configured to minimize channel head losses, to provide uniform head, and to optimize the discharge coefficient for the control structure crest.

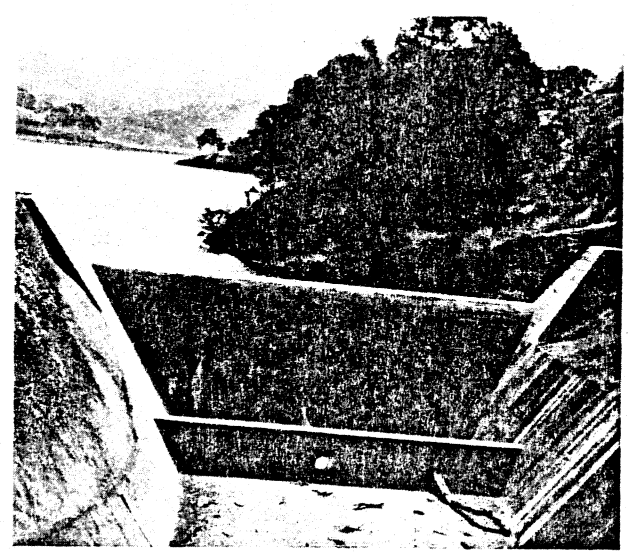

Figure 2-12. Spillway control structure

The control structure governs the reservoir outflow. Control structures may be an overpour crest in the form of a shaped weir or a sill, orifice-like openings, or conduit entrances. They may be either unregulated or regulated by gates, flashboards, and valves. Control structures are configured, positioned, and shaped in many different ways. Siphon control crests may sometimes be in use at older dams.

The discharge channel conveys and returns the water to the stream beyond the dam or into other topographic depressions beyond the reservoir basin. The channel may be on the face of a concrete dam; an open channel, lined or unlined, in natural formations; a conduit through or beneath the dam; or a tunnel through an abutment. Free falling outflows from overpouring crests require no discharge channel. Profiles, cross sections, alignments, and lengths are dimensioned and positioned in a variety of forms.

The terminal structure prevents undue erosion of the stream channel or damage to adjacent structures and the dam from the high-energy-laden spillway discharges. Stilling basins, roller buckets, baffled impact-type basins, and dentated aprons are commonly used for dissipating the energy as the flow returns to the stream. For efficient performance, their position in elevation with respect to tailwater elevation is critical. Where erosion resistant bedrock is present, releases may sometimes be made directly back to the stream at a distance from vulnerable structures. If the jet impingement can be predicted and controlled, the terminal structure can be a cantilevered or flip bucket extension of the discharge channel, provided that the impingement region and associated plunge pool will not endanger nearby structures or the bucket substructure.

Figure 2-13. Spillway discharge channel, terminal structure, and return channel

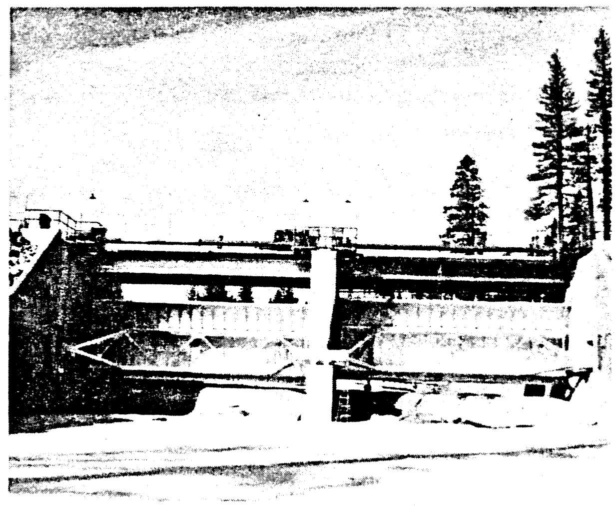

Figure 2-14. Radial gates at spillway control structure

The return channel conveys the flow back to the stream. The profiles and cross sections are dimensioned to avoid creating a hydraulic control that would adversely affect the energy-dissipating characteristics of the terminal structure and to provide velocities that minimize scour.

The spillway type and location are dependent upon the type of dam, site topography, geologic and foundation characteristics, and magnitude of expected floods. For example, spillways can be safely located on concrete dams, but it is not considered good practice to place them on major embankment type dams. A topographic saddle distant from the dam may provide a favorable location.

Spillway types are categorized by some distinctive characteristics of their components. The more common types are free-drop overflow, ogee overflow, open channel chute, side channel, conduit, tunnel, drop inlet, shaft, and siphon. Common classifications by use or operation are service, auxilliary, emergency, fuse-plug, controlled, and uncontrolled.

Controlled spillways often afford economic and operational advantages but they can also be hazardous at embankment dams if they fail to operate as planned. Redundant operational and alternative overflow relief features and seasonal variation of the level of the reservoir or the position of the control devices can sometimes reduce the probability of overtopping the dam should the system fail to function as planned.

Common control devices are radial gates, drum gates, Bascule-type gates, slide and wheeled gates, flashboards, stoplogs, soldier beams, and bulkheads. Two common types of gates are shown in Figures 2-14 and 2-15. The electrical, mechanical, and operational control systems for operating, installing, and removing headwater control devices range from simple to complex, and include local or remote, automatic or manual. Power sources may be hydraulic, commercial electrical, locally generated electrical, internal combustion engines, or a combination of these.

Outlet Works. Outlet works regulate the release of water from a reservoir and are sized and designed to meet the water demands and other purposes of the project. Releases of water are required for irrigation, municipal, industrial, and power generation use; for flood control regulation; for stream flow maintenance; and to satisfy prior or other downstream water rights.

Outlet works are usually classified according to (1) purpose such as canal outlets and pressure pipe outlets which divert water into canals and pipelines; river outlets which release water directly into the stream channel; flood control outlets which release water beyond the dam; and power outlets which admit water into tunnels and penstocks serving detached and integral power plants; (2) structural configuration - such as open channels or closed conduits; and (3) hydraulic operation - pressure or free-flow.

Outlet works are also used to lower the reservoir stage or empty the reservoir for inspection, maintenance, and precautionary reasons. Controlled, conduit type outlet works should not be considered as a spillway or part of the spilling capability for passing the spillway inflow design flood because of the uncertainties of availability and of absolute operational reliability during extreme floods.

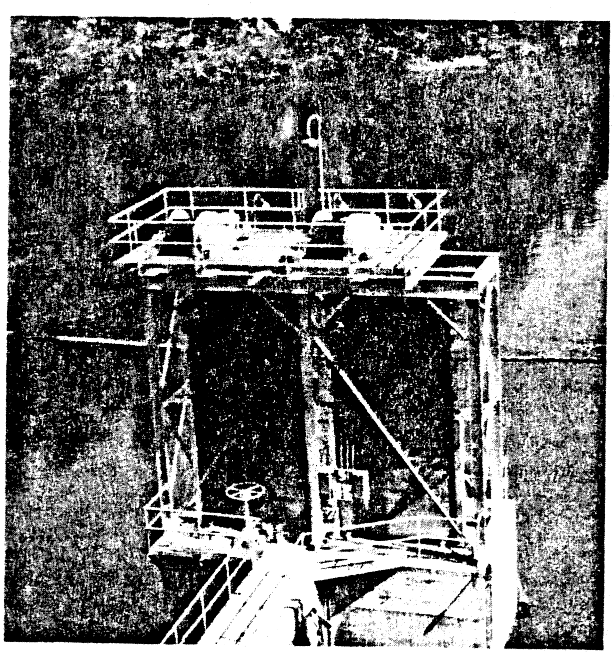

Figure 2-15. Roller gates for intake control structure

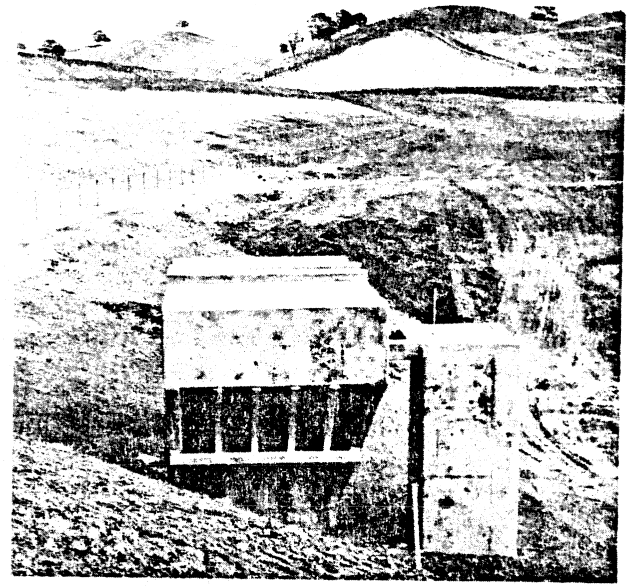

Figure 2-16. Intake structure of low-level outlet works

The type and location of the outlet works are dependent upon the purpose of the outlet, the type of dam, topographic, geologic and foundation characteristics, and the point of downstream release. Outlet works components which can be separately identified include the entrance channel; the intake structure; the waterway; the control structure; the terminal structure; and access shafts, bridges, and tunnels to operation and maintenance stations. Figures 2-16 and 2-17 show typical intake and terminal structures. The required components and their features are determined by the type, purpose, and location of the outlet works. A dam may have several outlet works for different purposes and they may be at different elevations.

The entrance channel conveys water to the intake structure of the outlet works. The intake structure establishes the ultimate drawdown level, guards against entry of trash, and may incorporate water control devices for flow regulation or closure devices for unwatering the outlet works during inspection and maintenance. 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 for siltation, the required amount and rate of withdrawal, and the desired extreme drawdown level.

The waterway conveys the released water from the intake structure to the point of downstream release. Waterways may be open channels, steellined sluiceways or ports through concrete dams, lined or unlined tunnels in abutments or from the reservoir basin elsewhere, or closed cut-and-cover conduits beneath the dam. Closed waterways may be designed for pressure and non-pressure flow. Pressure pipelines and penstocks may be extended through non-pressure conduits and tunnels, affording access and pressure relief.

The control structure regulates the flow of water through the outlet works and may be located at the upstream or downstream limits of the waterway, at intermediate positions, or at several positions. They house and support control devices which proportion or shut off outflow. Types of valves and gates used for control devices include slide gates; commercial gate valves; butterfly valves; ring follower, fixed-wheel, and roller train leaf gates; needle tube, jet-flow, hollow-jet, and Howell-Bunger valves; and bottom-seal and top-seal radial gates. For satisfactory performance, the type of valve or gate must be matched to service conditions such as maximum head, flow velocity, in line or free discharge, fully open or closed or partially open, and unbalanced or balanced head operation. The operational control systems are similar in principle to those discussed above for spillways.

The terminal structure delivers the flows to the point of downstream release. Any need for and the type of terminal structure is determined by the purpose of the outlet works. For river and flood control outlets the terminal structures can be similar in principle to those for spillways or the outlet releases may be conveyed through the spillway terminal structure. Normally, terminal structures are unnecessary for pipe, canal, and power outlets.

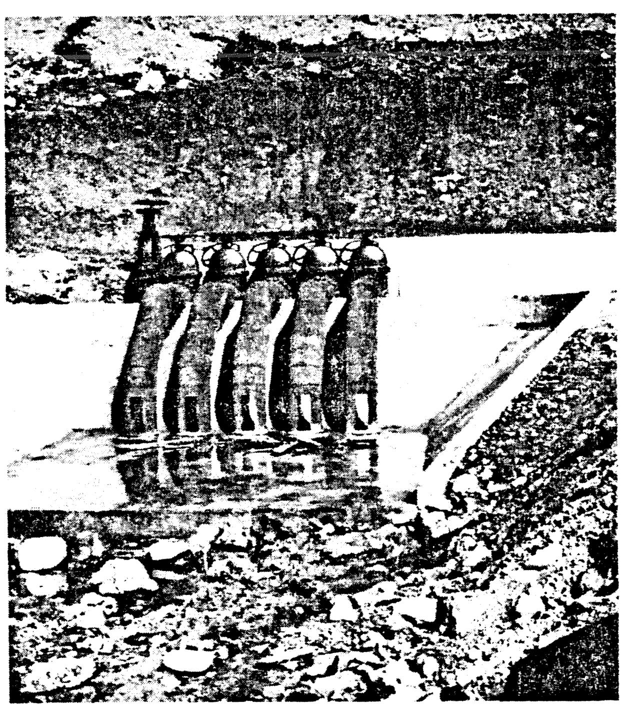

Figure 2-17. Terminal structure of outlet works

The access component may be a bridge from the dam crest to a tower intake structure, a vertical cast or drilled shaft from the ground surface to a valve chamber in a conduit or tunnel, an inclined tunnel, roadways and bridges to control structures and houses at the downstream end of the waterway, or galleries and ladders at concrete dams.

Power Plant. A power plant may be hydraulically and/or structurally coupled to a dam. The intake and penstock water passages for the plant may be formed within the body of a concrete dam, or the plant penstock may be appended to the face of the dam. The plant enclosures may be formed by the buttresses and face elements of a buttress-type dam, or the plant substructure and enclosure may create a water barrier auxiliary to or in conjunction with the actual dam. An underground plant may be located within the dam abutment mass. Economic advantages from reduced head losses and hydraulic transient control associated with plant operation are possible with these close coupled arrangements.

It is unlikely that these coupled arrangements will be encountered at existing impoundments under study for small hydropower. If they are, the existing plant elements must be evaluated for their impoundment integrity. If they are not, it is unlikely that any proposed power plant facilities would replace portions of the existing dam as a primary water barrier. Instead, the dam modifications would likely be those to accommodate power outlets for structurally detached power plants.

Navigational Locks. A navigational lock may form a portion of a dam. It is subject to the same gravity, seismic, seepage and hydraulic forces as a dam. The lock is usually joined to adjacent earth, rockfill, or gravity sections of the actual dam.

The facilities controlling admission and discharge of water for the lock chamber and the lock gates are hydraulically and structurally similar in many ways to the control devices and gates for outlets and spillways. The same engineering design and performance principles can be applied in their integrity investigation.

Fish Ladders and Log Sluices. Facilities for fish and log passage through or over dams are also similar to outlets and spillways in their hydraulic performance and manner of control. Their integrity for safe impoundment is structurally investigated employing the same techniques used for outlets and spillways. Examples are shown in Figures 2-18 and 2-19.

References. Several of many excellent references in the literature of dam engineering amplify, discuss in detail, and present examples of the principles and descriptions discussed in this portion (Golze, 1977; Justin et al., 1945; U.S. Department of Interior (USBR), 1974/1; *et passim*).

Figure 2-18. Fish ladder at flashboard and buttress dam

Common Deficiencies or Failure Modes Associated with Small Existing Dams

Many existing dams may have significant deficiencies or may be subject to failure, even though they have performed satisfactorily for decades. The state of the art in dam design and construction has advanced considerably from the past and many older dams do not meet present standards. Furthermore, dams, appurtenant works, and their foundations are subject to aging and deterioration; or potential problems may develop when the operating conditions of the dam change. Deterioration of the dam and related structures may be readily apparent, or the deterioration may be very subtle and not manifest itself until substantial damage has occurred and failure becomes imminent. Several typical dam deficiencies or failure modes are listed below.

1. Dam overtopping
2. Piping
3. Uncontrolled and excessive seepage
4. Foundation instability
5. Embankment slope instability
6. Deterioration of slope protection on embankment dams
7. Deterioration of concrete
8. Excessive hydraulic uplift pressures
9. Spillway and outlet failure or inadequacies
10. Erosion.

One of the most common modes of small dam failure is recognized to be due to overtopping. This is due to the inadequacy of, or lack of, spillways in many old, existing structures. The effects of overtopping on different types of dams can vary considerably. Overtopping can cause serious distress and even the total failure of earthfill structures. In the case of concrete dams, uncontrolled overtopping can damage or destroy the abutments and/or structures or appurtenant works immediately downstream of the dam and can cause erosion and scour downstream of the structure. Many old, stonewall earth dams have been subjected to reported minor overtopping without significant damage to the structure.

Reservoir slides can cause large waves that can overtop the dam. Reservoir slide debris can also block outlets and spillways, leading to overtopping.

Spillway and outlet failures and malfunctions can lead to dam overtopping. Spillway and outlet facility criteria are discussed in Section 3.

A form of erosion known as piping is caused by the movement of soil particles to unprotected exits due to uncontrolled seepage. Piping failures are recognized to be a very common mode of failure of dams. Piping can occur through embankments or through a dam's foundation or abutments. Areas adjacent to conduits are particularly susceptible to piping because of the difficulty in properly compacting backfill around these conduits. Piping problems have developed at dams with many years of satisfactory performance due to solution of soluble materials (such as gypsum) within the dam abutments and foundations. Similar problems have resulted from animal burrows and rotted tree roots. Differential settlement cracks can also provide paths for uncontrolled seepage with attendant erosion.

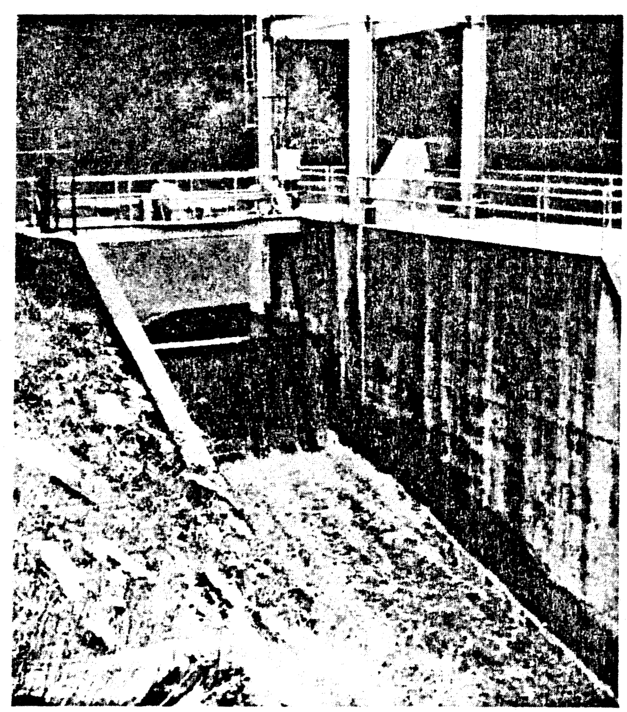

Figure 2-19. Log chute (debris skimmer)

Such uncontrolled foundation seepage can lead to high uplift pressures or uplift pressure distributions not anticipated during the design of the dam. Such excessive pore water pressures can lead to the formation of boils and springs and, by reducing the shearing resistance, to the failure of abutments and slopes.

Problems that are associated with adverse foundation conditions include slides, differential settlements, and excessive seepage. Foundation slides have occurred where foundation materials have low shear strength or where seams of weak material exist in an otherwise competent foundation. Differential settlements of compressible foundations can lead to excess cracking in the dam. Pervious seams and adverse bedding planes can provide paths for uncontrolled seepage. Foundation problems can also result from deteriorating grout cutoff curtains and plugged relief wells or drains.

Embankment slope instability can lead to catastrophic failure of a dam. The most common cause of slope instability is the development of excess pore water pressures due to unfavorable seepage conditions. Dams with many years of satisfactory performance can develop slope stability problems when operating conditions change, such as drawdown of the reservoir, or when embankment material properties change due to aging.

Embankment dam slopes are subject to erosion from wave action on the upstream slope and from surface runoff on the downstream slope. Riprap slope protection can suffer degradation from wave action, slaking, and decomposition. When riprap is placed directly on embankment surfaces without suitably graded bedding or filters, the underlying embankment materials can be washed out, causing sinkholes and riprap sloughing.

Numerous concrete and masonry structures have exhibited substantial deterioration of structural concrete and grout. Deterioration of concrete from alkali-aggregate reaction, sulfate attack, freeze-thaw deterioration and leaching of soluble substances from the cement are typical problems that may develop in concrete dams. This deterioration (or, sometimes, poor construction practices) can lead to vuggy (cavitated) concrete, "popcorn" concrete, areas with mortar and no aggregate, and areas of aggregate and no mortar.

Alkali-aggregate reaction can lead to concrete deterioration well within the interior of structures, greatly reducing the concrete strength. Freeze-thaw deterioration is generally concentrated on concrete surfaces.

Over-stressing and differential displacements of concrete structures create areas of distress and cracking where freeze-thaw action or leaching of the concrete can lead to further deterioration of the structure.

Concrete deterioration and cracking can lead to exposure of steel reinforcement. Corrosion of steel reinforcement with subsequent loss of strength, along with loss of concrete strength, has been a problem with some buttress dams.

Dams located in seismically active regions may be subjected to severe shaking or foundation displacements due to fault movement. Seiches (seismically induced water waves) may cause overtopping. Seismic shaking causes an increase in pore pressures in impervious or semi-pervious materials and a resulting decrease in shear strength. The decrease in shear strength, coupled with the seismically induced shear stresses, can lead to the failure of the dam. Other earthquake effects may be cracking of embankments or excessive settlements, the former providing direct paths for water flows with resultant erosion and possible breaching, and the latter leading to loss of freeboard and possible overtopping.

The more unusual types of dams can be subject to unique problems. Timber dams are subject to deterioration of the wood timbers. The rate of deterioration depends on the type of wood used and on dam operation. Redwood timbers generally have a longer life than cedar. Timbers that are repeatedly wetted and dried deteriorate at much greater rates than timbers kept continuously wet. Stonewall earth dams have been known to fail due to frost heave.

Adverse Effects of Power Additions

Any modification of existing dams, appurtenant structures, reservoir conditions, or the area near these facilities will modify stresses within the components. Some modifications resulting from the addition of hydroelectric facilities would have an adverse effect on the integrity of the existing facilities. Changes in reservoir operating conditions and the possible effects on the reservoir area are discussed above, and the effects of adding hydroelectric facilities to the existing facilities are discussed briefly below. Methods of investigating and rehabilitating existing facilities are discussed in Sections 3 and 4 of this volume.

The most common problems that have been encountered in adding hydroelectric facilities to existing structures have been associated with utilizing existing outlet conduits or installing new water passages and making excavations for the power facilities downstream of the dam.

The existing outlet facilities form the most obvious waterway from the impoundment to the powerhouse, and also the least expensive to construct. However, there are several pitfalls in using these facilities as a penstock. Conduits with controls at the upstream end or at intermediate points were probably not designed for and are not capable of withstanding the full hydrostatic head created by the reservoir. If the controls are moved to the downstream end (as is normally done when power facilities are added), full reservoir pressure will exist in the conduit when power is not being generated, and when the powerhouse is in operation the internal pressures will be higher than normal for a dam conduit. At several facilities, it has also been found that the outlet conduits can be inadequate for other reasons: the small diameter of the conduit may cause excessive energy loss, or cavitation may occur because of abrupt changes in alignment.

If the existing outlet facilities are inadequate for power generation, a new water passage must be constructed or the inadequate portion replaced or modified. Small diameter conduits buried under earth and rockfill dams are not amenable to modification, and generally the only practical means of adding a new water passage to an earth or rockfill dam is by tunneling through an abutment. On the other hand, it is practical to construct a water passage through a concrete dam. However, a structural analysis of the changed condition should be performed, since the introduction of an opening in the concrete may result in overstressing portions of the structure. If blasting is required to drive a tunnel through or remove concrete from an existing structure, the charges must be controlled so that the structure and foundation are not damaged.

Each existing facility is unique and good engineering judgment must be used to evaluate and solve problems in adapting water passages for use in hydroelectric generation. For example, at one site, a diversion tunnel which had been constructed through one abutment during initial construction was successfully adapted for hydropower use. The tunnel had been plugged with concrete near the axis of the dam, with a small diameter steel conduit extending through the plug to a point downstream of the dam. It was concluded that excessive energy losses would occur if the samll diameter conduit was used for power generation. The solution was to blast an opening in the plug, reseal the plug around a larger diameter steel pipe, and extend the pipe through the tunnel to the powerhouse. Construction specifications limited the energy release during blasting and instruments were used to record accelerations when blasting was performed.

As well as structural and hydraulic problems, environmental problems may occur when existing outlet facilities are utilized. At one such facility, where only a low level intake existed, it was determined that, at certain times of the year, water releases from that level were deficient in dissolved oxygen and aquatic life for some distance downstream of the powerhouse would be destroyed. Either a multiple level intake structure needed to be added or the water aerated before release from the powerhouse area.

The addition of power facilities downstream of the dam will require regrading of the area. Building up the area at the toe of the dam will generally not reduce the stability of the dam if drains or other seepage outlet paths are not blocked off. Excavations within the influence area of the dam will result in weakening the existing facilities and increasing the potential for sliding, foundation failures, and piping problems. As a general rule, for planning and feasibility purposes extensive excavations which are over 5 feet deep should not be performed close to the downstream toe of the dam. A distance of at least one half the height of the dam should be maintained between the downstream toe and the upstream edge of an excavation in solid rock. This distance should be increased to at least the full height of the dam when the excavation is in soft rock or soil. Where this is impractical, rock stabilzation techniques may have to be used. Where foundation conditions are poor or questionable, a subsurface exploration program should be conducted and an evaluation made of the effects of excavation in the vicinity of the dam. Prior to final design and construction, a subsurface exploration program must be conducted and an evaluation made of the effects of excavation in the vicinity of the dam regardless of the type of foundation material.

The addition of power facilities at the toe of the dam may require relocation of the spillway so that it does not discharge in the powerhouse area. If spillway discharges can be directed to an adjoining valley, this may be the best solution to the problem. Otherwise flow from the spillway must be carried past the powerhouse and the power facilities will have to be protected from backwater during flood discharges. The area downstream of the dam and power facilities must be protected from erosion by discharges from the spillway and tailrace.