Training
Aids for
Dam
Safety

MODULE:

EVALUATION OF CONCRETE DAM STABILITY

TADS

Training Aids for Dam Safety

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EVALUATION OF CONCRETE DAM STABILITY

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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-student 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, dam 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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MODULE INTRODUCTION

MODULE INTRODUCTION

OVERVIEW OF THIS MODULE

This module provides information about static and seismic stability of concrete dams. The focus is primarily on gravity-type dams. It addresses the following general topics:

- The purpose of evaluating the structural stability of existing concrete dams
- Methods that may be used in conducting static and seismic stability analyses
- Potential remedial measures

The information will be useful to those who deal with the safety of concrete dams and their appurtenances, including concrete spillways, outlet works, and other structures.

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 six units followed by two appendixes:

- **Unit I. Overview:** Presents information on the types of concrete dams, the nature of static and seismic stability, and modes of static and seismic stability failure.
- **Unit II. Review And Evaluation Of Project Data:** Describes the project data that should be reviewed to determine the current validity of assumptions regarding a dam's design loading, and whether weaknesses or conditions exist that presently threaten the stability of the dam or could do so under design loading.
- **Unit III. Analysis Considerations:** Describes key factors to be considered before analyzing the static and seismic stability of a concrete dam.
- **Unit IV. Static Stability:** Provides an overview of methods used to evaluate static stability.
- **Unit V. Seismic Stability:** Provides an overview of methods used to evaluate seismic stability.

MODULE INTRODUCTION

CONTENTS OF THIS MODULE (Continued)

- **Unit VI. Remedial Action:** Describes emergency and temporary measures and long-term remedial measures that may be used to deal with a potentially unstable concrete dam.
- **Appendix A. Glossary:** Defines a number of technical terms used in this module.
- **Appendix B. References:** Lists recommended references that can be used to supplement this module.

DESIGN OF THIS MODULE

This module is comprised of text instruction only. There is no accompanying video presentation.

UNIT I

OVERVIEW

I. OVERVIEW: INTRODUCTION

INTRODUCTION

A concrete dam must be able to safely withstand the static forces that tend to cause sliding or overturning, as well as the additional dynamic forces induced by the ground motions of the design earthquake. If you are an owner or otherwise have responsibility for a concrete dam, you should know whether that dam is stable under all potential loading conditions. To verify a dam's stability, investigations and analyses may be necessary.

This unit provides background information about types of concrete dams and the significance of static and seismic stability of concrete dams. It also describes modes of static and seismic stability failure.

I. OVERVIEW: BACKGROUND INFORMATION

INTRODUCTION

A concrete dam is a dam constructed mainly of cast-in-place or roller-compacted concrete. There are three major types of concrete dams, as shown in Figure I-1: gravity dams, arch dams, and buttress dams.

- A **gravity dam** is a massive concrete structure, roughly triangular in shape, and designed so that its weight ensures structural stability against the hydrostatic pressure of the impounded water and other forces that may act on the dam. Gravity dams may be classified by plan as straight gravity dams and curved gravity dams, depending upon the axis alignment.

- An **arch dam** is a solid concrete structure, usually thinner than a gravity dam, that is arched upstream. An arch dam obtains most of its stability by transmitting the reservoir load into the canyon walls by arch action.

- A **buttress dam**, a form of gravity dam, is comprised of two or three basic structural elements: a watertight upstream face, buttresses that support the face and transfer the load from the face to the foundation, and sometimes a concrete apron. Buttress dams depend on their own weight and the weight of the water acting on the upstream face to maintain stability.

Another type of dam that may require evaluation is the **masonry dam.** A masonry dam is constructed mainly of stone, brick, rock, or concrete blocks joined with mortar. Most masonry dams are older gravity dams, although a few are arch dams.

Each type of dam may fail due to static or seismic instability, and an evaluation should be made of a particular dam's susceptibility to such instability.

STATIC AND SEISMIC STABILITY

Concrete dams are subject to various loads, including external and internal water pressures, earth pressures due to siltation, ice pressures, and earthquake forces. Stability analyses are performed to ensure that the dam and its foundation are capable of safely accommodating these loads.

Two major classifications of stability are discussed in this module: static stability and seismic stability.

- **Static Stability:** Ability of a dam to resist the static forces that tend to induce sliding or overturning.

- **Seismic Stability:** Ability of a dam to resist the additional dynamic forces induced by the ground motions of an earthquake.

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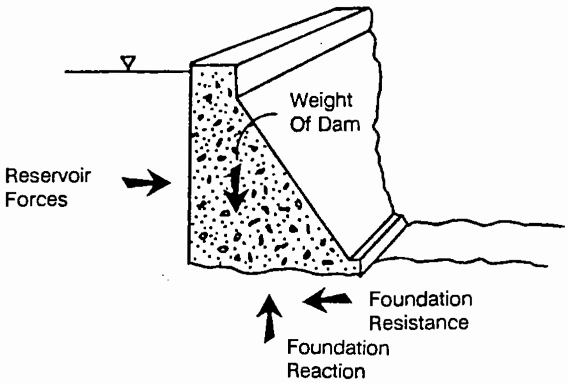
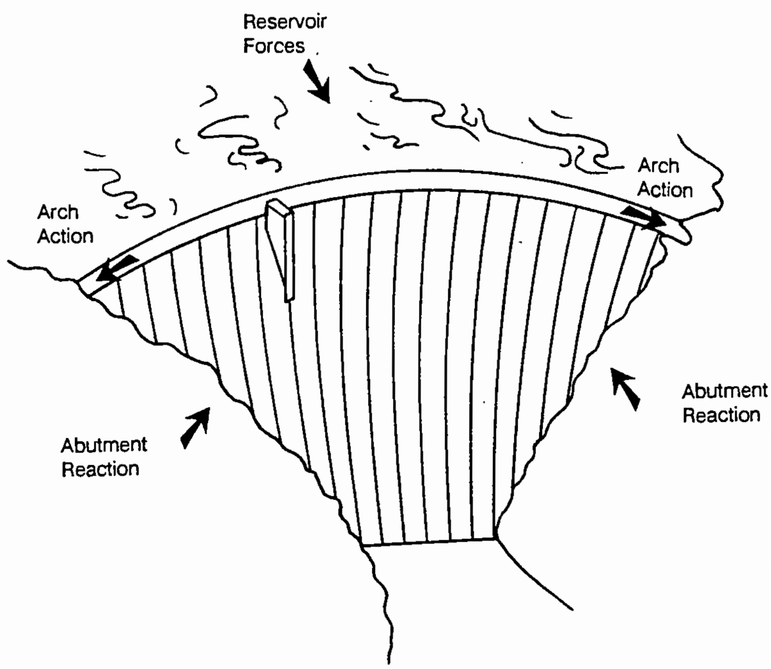
STATIC AND SEISMIC STABILITY (Continued)

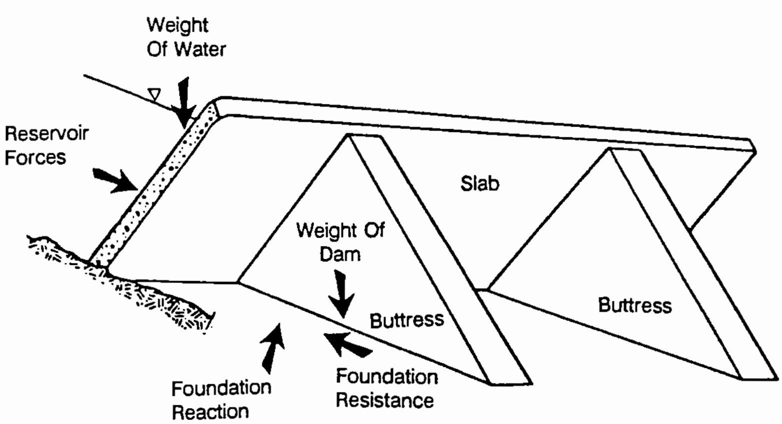
FIGURE I-1. TYPES OF CONCRETE DAMS



GRAVITY DAM



ARCH DAM



BUTTRESS DAM

Continued . . .

STATIC AND SEISMIC STABILITY (Continued)

Discussions in this module focus primarily on the evaluation of gravity dams. Except where stated otherwise, the concepts may be applied to other types of dams as well, and significant differences are discussed. In the case of straight and curved gravity dams, the principal differences are that a straight dam would be analyzed by one of the gravity methods whereas a curved gravity dam may be analyzed either by one of the gravity methods or by arch dam analysis methods.

HISTORICAL PERSPECTIVE

Concrete (or masonry) dams have some inherent advantages over embankment dams. They require less, albeit more expensive, construction material, and they are resistant to overtopping and to internal erosion by seepage. On the other hand, they generally require more competent foundations and abutments because of their rigidity.

Historically concrete dams are relatively safe when compared to their earthfill and rockfill counterparts. This is because of their inherent durability and high resistance to erosion. Seepage and overtopping situations that would cause failure in an earthfill or rockfill dam would not, in most cases, cause a concrete dam to fail. Nevertheless, there still have been significant failures of all types of concrete dams continuing into recent times. Most failures can be traced to overstress of foundations or abutments because the in situ materials were not adequate to sustain the applied loads or deteriorated as seepage developed. Deterioration of concrete and particularly of the mortar in older masonry structures has also resulted in several failures.

I. OVERVIEW: MODES OF STATIC STABILITY FAILURE

INTRODUCTION

Static failure of concrete gravity dams can generally be divided into two broad categories: sliding and overturning. The dam's ability to resist sliding and overturning can be compromised by concrete deterioration and concrete distress.

Although sliding and overturning stability are investigated for various planes through the body of the dam, most of the problems with concrete dams are associated with the foundation. The foundation for a gravity dam must be capable of resisting the applied forces without overstressing the dam or the foundation itself. The horizontal component of reservoir hydrostatic load acting on the dam tends to make the dam slide in a downstream direction, which results in shear stresses within the dam and along the base of the dam. These stresses may induce concrete shear failure on horizontal planes within the dam, at the base or along the concrete-rock contact, or within the rock foundation. Uplift forces induced by seepage pressure, in combination with the horizontal hydrostatic forces, tend to overturn the dam, which in turn may cause overstressing and crushing of the rock along the toe of the dam. Table I-1 provides a more detailed overview of the causes of static stability failures of concrete dams.

TABLE I-1. CAUSES OF CONCRETE DAM INCIDENTS
(Number Of Cases*)

Cause	Type Of Dam								
	Arch		Buttress		Gravity		Totals		
	F	A	F	A	F	A	F	A	F&A
Overtopping	2	1	1		3	2	6	3	9
Flow Erosion	1		1		1		3		3
Foundation Leakage, Piping	1	1	2		2	5	5	6	11
Sliding					2		2		2
Deformation		2						2	2
Deterioration		3		2		1		6	6
Faulty Construction					2		2		2
Gate Failure					1	2	1	2	3
TOTAL	4	7	4	2	11	10	19	19	38

* For dams higher than 15 meters and completed after 1900.
F = Failure
A = Accident: An incident where failure was prevented by remedial work or operating procedures, such as drawing down the reservoir.

SOURCE: Compiled from Lessons From Dam Incidents (USA, ASCE/USCOLD 1975), and supplementary survey data supplied by USCOLD.

I. OVERVIEW: MODES OF STATIC STABILITY FAILURE

SLIDING FAILURES

Figure I-2 depicts typical sliding failures. Sliding failures more often result from deficiencies in the foundation, as in Figure I-2(b). Various foundation conditions can make a concrete dam vulnerable to sliding failure:

- Low foundation shear strength
- Bedding planes and joints containing weak material, such as clay or bentonite
- Seams of pervious material, if seepage through them is not controlled to prevent detrimental uplift
- Faults and shear zones

Bedding planes and joints frequently have caused problems at dam sites and therefore warrant close examination. Two common types that have been troublesome are bedding-plane zones in sedimentary rocks and foliation zones in metamorphics.

For a gravity dam, the potential for sliding may be greatest when the foundation rock is horizontally bedded, particularly where there is low shear strength along the bedding planes. Consideration also must be given to zones within the foundation rock that are especially susceptible to the development of unacceptable seepage uplift forces.

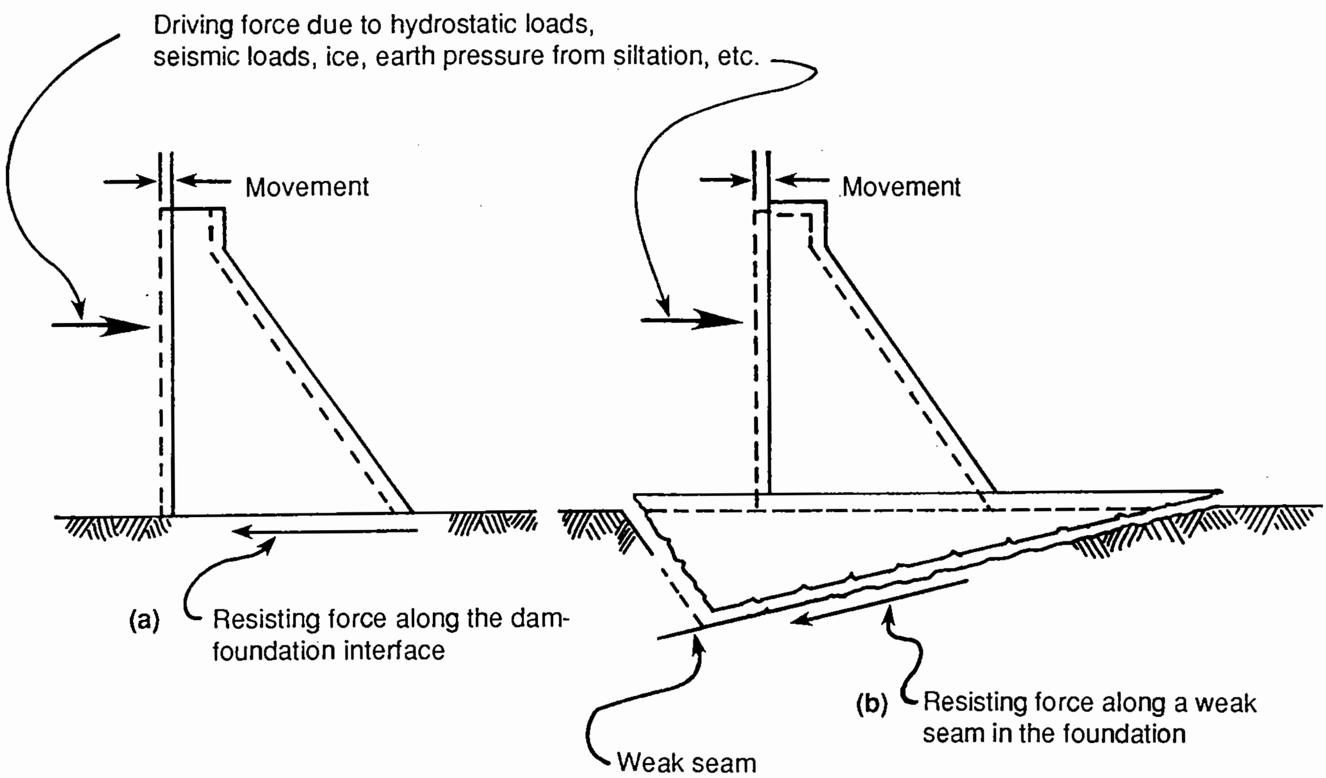
A situation that can lead to detrimental uplift is illustrated in Figure I-3. Because the dam tends to move downstream, tensile stresses are created in the foundation which may cause upstream joints and cracks to open and allow seepage to enter. The resulting uplift can lead to sliding or overturning.

Continued . . .

I. OVERVIEW: MODES OF STATIC STABILITY FAILURE

SLIDING FAILURES (Continued)

FIGURE I-2. SLIDING FAILURE:
DRIVING FORCE EXCEEDS SAFE RESISTING FORCE



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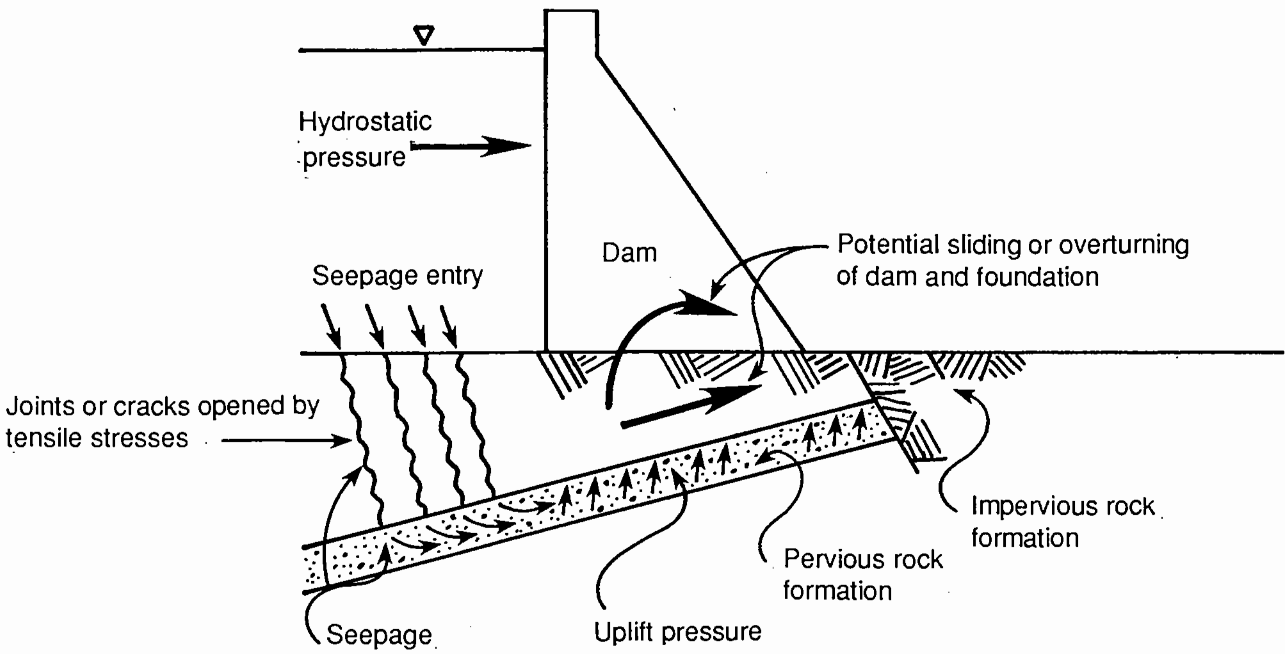
SLIDING FAILURES (Continued)

FIGURE I-3. HIGH UPLIFT PRESSURE



I. OVERVIEW: MODES OF STATIC STABILITY FAILURE

OVERTURNING FAILURES

Overturning failures have various causes:

- **Insufficient weight** or improper distribution of weight in the dam cross section to resist the applied forces. This situation can cause high compressive stresses at the toe of the structure and/or high tensile stresses at the heel. Crushing of the concrete or foundation material at the toe may occur as a result of the high compressive stresses.

- **Tensile cracking** over portions of the base of the structure which is not in compression, resulting in high uplift forces and a loss of resistance to overturning.

- **Erosion** of the rock foundation at the toe of the dam due to overtopping or rock deterioration.

- **High uplift pressures** caused by inadequate seepage control or pressure relief.

- **Excessive hydrostatic pressures** due to severe flood conditions, resulting in higher reservoir levels than the dam was designed to accommodate.

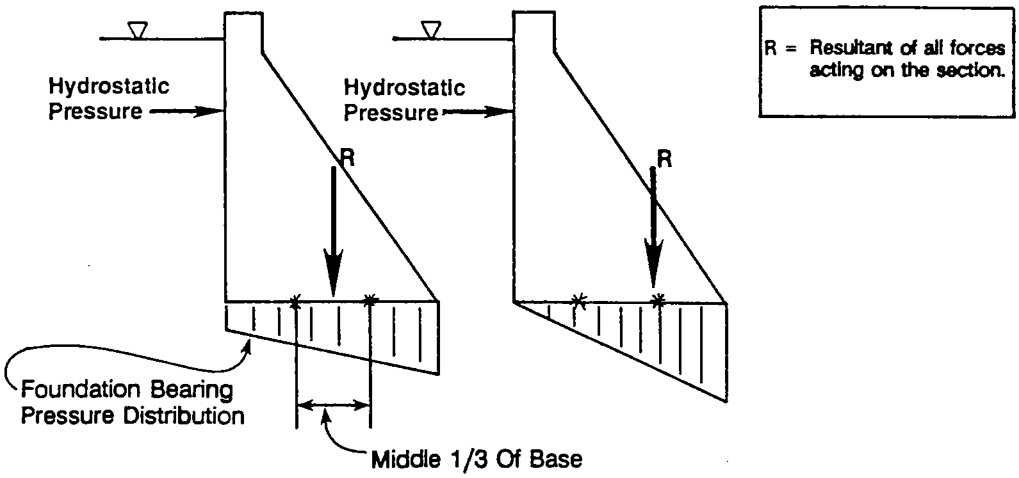
Figure I-4 depicts safe and unsafe conditions with regard to overturning stability. Overturning stability is dependent upon the location of the vertical component of all applied loads with respect to the toe of the dam.

I. OVERVIEW: MODES OF STATIC STABILITY FAILURE

OVERTURNING FAILURES (Continued)

FIGURE I-4. OVERTURNING STABILITY

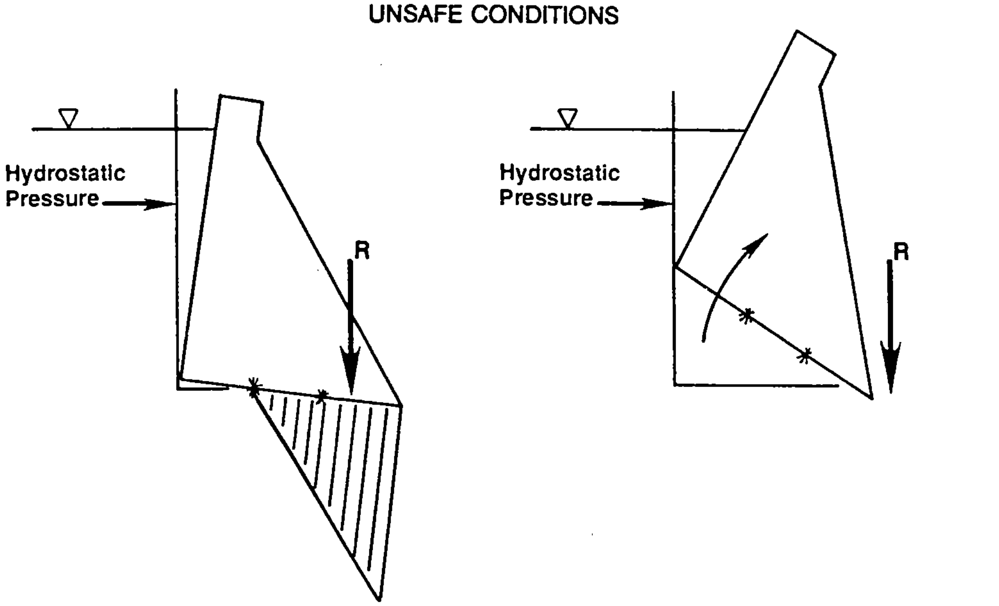
SAFE CONDITIONS



(a) Resultant in middle 1/3 of base; 100% of base in compression.

(b) Resultant at middle 1/3 of base; 100% of base in compression.

UNSAFE CONDITIONS



(c) Resultant outside middle 1/3 of base; loss of contact at heel; high bearing pressures at toe.

(d) Resultant outside base; dam overturns.

I. OVERVIEW: MODES OF STATIC STABILITY FAILURE

CONCRETE DETERIORATION

Deterioration of the concrete in dams may be caused by environmental or chemical processes. These processes may occur more quickly if inferior materials or placement techniques were used during construction of the dam.

Environmental Factors

Environmental factors that cause deterioration of concrete include freeze-thaw action, thermal expansion and contraction, and wet-dry cycles. For additional information on concrete deterioration caused by environmental factors, you may wish to refer to the TADS inspection module Identification Of Material Deficiencies.

Chemical Factors

Chemicals, both from within the concrete and from outside the structure, can reduce the strength of concrete or otherwise damage it. Alkali-aggregate reaction damage is a common example of damage caused by chemical reactions within concrete. When high amounts of alkali in the cement react unfavorably with aggregate in the concrete, the chemical reaction can cause the concrete to expand, resulting in cracking and deterioration.

External chemicals can also cause damage. For example, water containing inorganic acids or sulfates can enter the concrete through cracks or joints. These chemicals can react with the cement, aggregate, or reinforcing steel near the surface of the concrete and cause deterioration.

For additional information on concrete deterioration caused by chemical factors, refer to the TADS inspection module Identification Of Material Deficiencies.

Defective Or Inferior Concrete

Substandard concrete may result from using inferior materials or procedures in preparing or placing the concrete. Inferior concrete may result from many causes, including:

- Poor consolidation and curing
- Poor bond at lift lines
- Weak aggregates
- Mineral-laden water
- Highly absorptive aggregates, which may be susceptible to freeze-thaw damage
- Aggregates contaminated by soils, salts, mica, or organic material
- High cement content, leading to high internal temperatures due to hydration
- Insufficient pre or post cooling of concrete
- High water/cement ratios in concrete mix
- Lack of entrained air
- Reactive aggregates

I. OVERVIEW: MODES OF STATIC STABILITY FAILURE

Defective Or Inferior Concrete (Continued)

Many gravity dams built in the nineteenth century were constructed of stone masonry with lime mortar. Lime mortar is susceptible to deterioration and loss of strength over long periods of exposure to seeping water. Once the bond between stones created by the mortar has been broken, water may enter the joints and the resulting pressure can cause a sliding or overturning failure.

CONCRETE DISTRESS

Cracking of concrete structures may result from excessive tensile or compressive stresses, high impact loads such as barges or ice, or differential movements of foundation and abutment materials. In spillways or outlet works conveying high velocity flows, offsets in the concrete surfaces may cause cavitation. Vibration of structures by earthquake, water surges, or equipment operation may also damage concrete.

ARCH DAM FAILURES

Concrete arch dams are usually high in relation to their length, and their safety depends greatly on the competence of the abutments. Failure of arch dams often results from a weakness in the bedrock of the abutment that supports the arch. The failure is frequently induced by displacement of the foundation or abutment or by the erosion of the foundation or abutment when the dam is overtopped. An initial break usually develops into a complete failure of the dam.

Figure I-5 illustrates foundation displacement in an arch dam failure.

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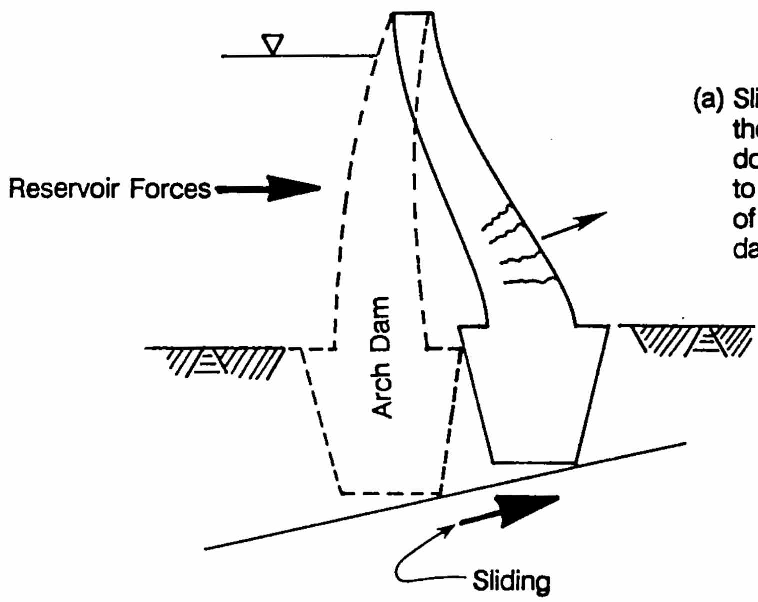
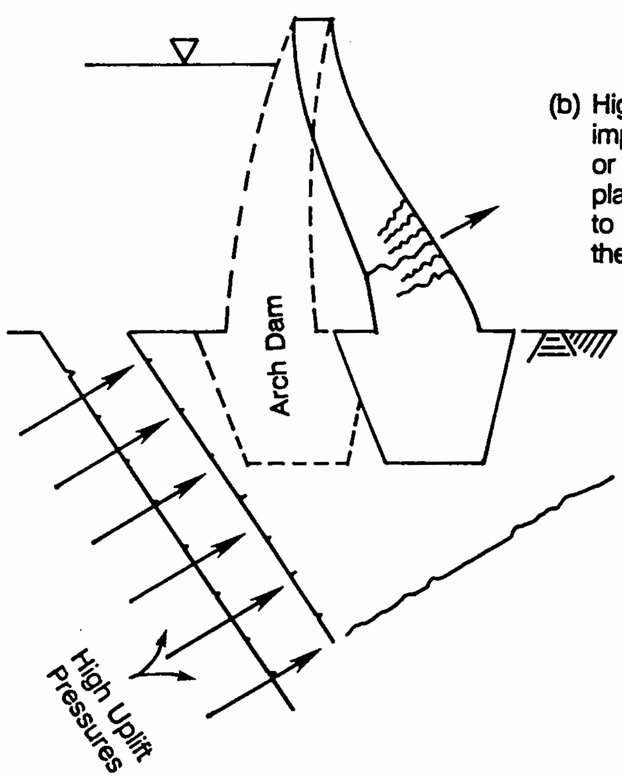
I. OVERVIEW: MODES OF STATIC STABILITY FAILURE

ARCH DAM FAILURES (Continued)

FIGURE I-5. ARCH DAM FAILURES



(a) Sliding along a zone of weakness in the foundation or abutment causes a downstream displacement which leads to high concrete stresses and failure of the arch dam. As a result the dam is breached.



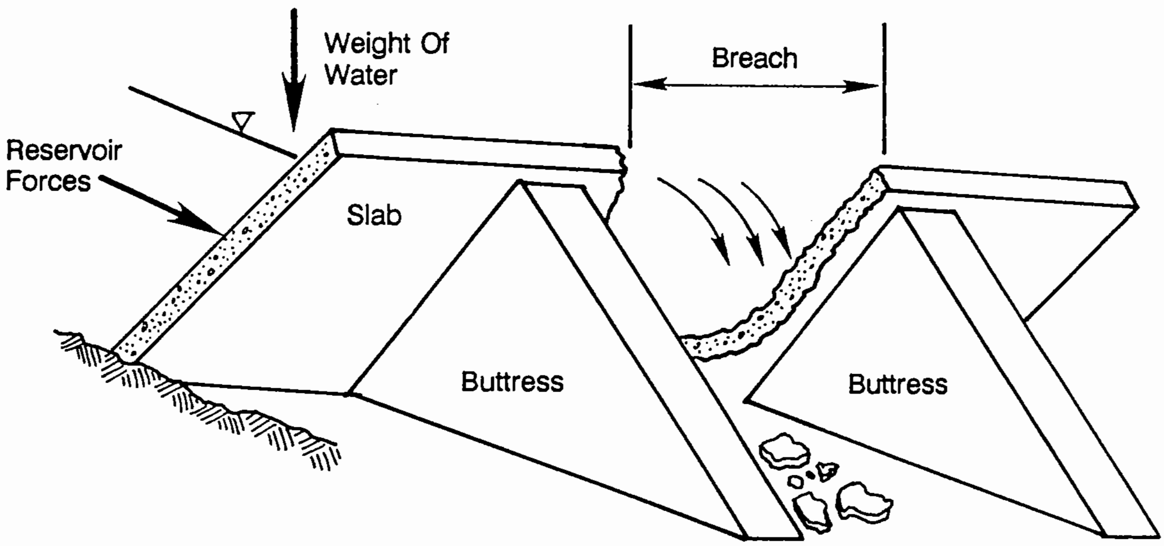
(b) High uplift pressures develop along an impervious barrier in the foundation or abutment causing a downstream displacement of the foundation which leads to high concrete stresses and failure of the arch dam.

I. OVERVIEW: MODES OF STATIC STABILITY FAILURE

BUTTRESS DAM FAILURES

The design of buttress dams built 50 to 70 years ago may not meet current standards. In some cases the strength of the concrete and steel reinforcement may be inadequate. When compared to gravity dams, concrete deterioration of buttress dams is more critical because the slabs and buttresses are relatively thin. If one of these members fails, an entire section of the dam may be lost, as illustrated in Figure I-6.

FIGURE I-6. BREACHING FAILURE—BUTTRESS DAM



I. OVERVIEW: MODES OF SEISMIC STABILITY FAILURE

INTRODUCTION

Concrete dams have performed extremely well during earthquakes, even when subjected to loads far in excess of those used in the design. However, marginal static stability with respect to sliding, overturning, and concrete distress may lead to instability under dynamic loading. Dynamic loading can be a more severe loading condition because of the following factors:

- The additional loads caused by the inertial effects of the dam and reservoir

- Possible strength loss of dam foundation materials under cyclic loadings

Concrete dams subjected to earthquake-induced dynamic loadings must be evaluated for three main modes of seismic failure:

- Internal failure
- Foundation failure
- Secondary events

INTERNAL FAILURE

The ground motions of an earthquake subject a dam to dynamic loads. Dynamic loads are essentially inertial forces related to the mass, flexibility, and damping characteristics of the dam. In addition, increased driving forces are exerted on the upstream face of the dam by the hydrodynamic response of the reservoir. Figure I-7 illustrates the behavior of a concrete gravity dam during a major earthquake. It should be remembered that the ground motion is random in magnitude and direction and cyclic in nature.

The dynamic compressive and tensile strengths of concrete are significantly higher than the static strengths. This difference is due to the rapid loading rate of seismic events. The ability of a concrete dam to resist a major earthquake is highly dependent on the tensile strength of the concrete. The high strain rates associated with earthquakes can provide tensile strengths up to 50 percent greater than those associated with static loads, thereby increasing the dam's ability to resist the damaging effects of the earthquake.

Analyses of existing dams that have been subjected to earthquake loadings show that high tensile stresses can develop at corners and geometric discontinuities. High tensile stresses are the principal cause of cracking in concrete dams. Cracking caused by earthquakes often occurs where there are abrupt changes in configuration that result in stress concentrations. Cracking also occurs in the concrete near the crest of the dam where the largest amplification of ground motion occurs. The cracks generally run in a horizontal direction. Cracking during a major earthquake is allowable and not unusual. However, a dam must be able to retain the reservoir for a sufficient period of time after the earthquake to allow for drawdown of the reservoir or other remedial action, if necessary.

Existing dams in high seismic zones may require a rigorous analysis in order to accurately predict dynamic tensile stresses and the dam's response to ground motion.

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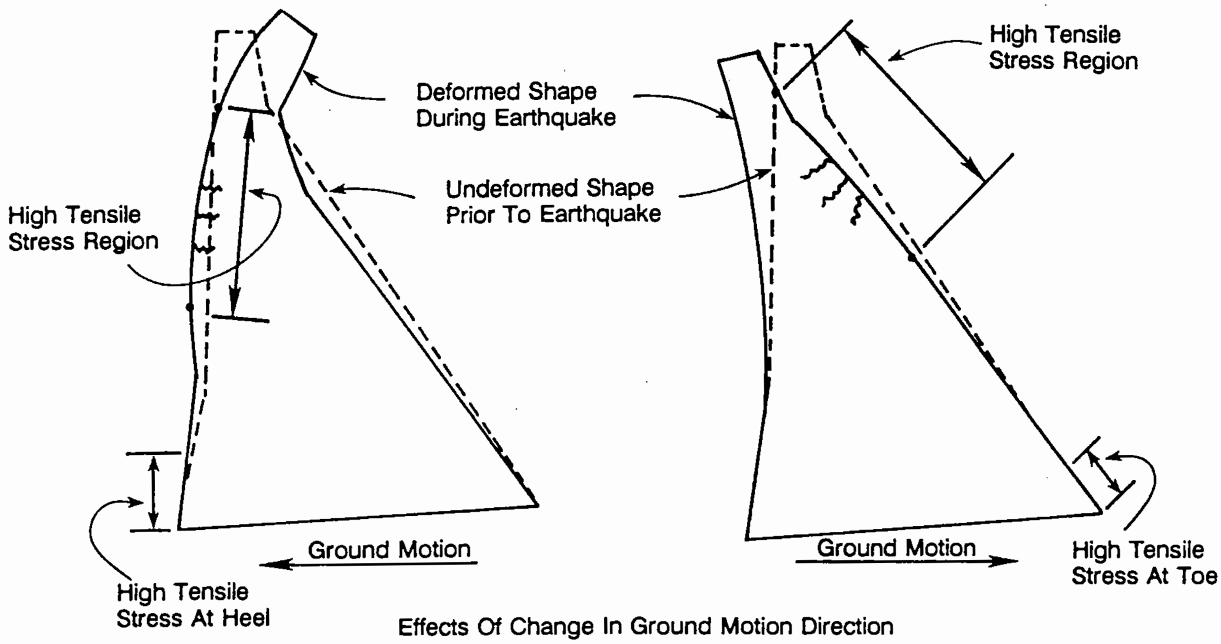
INTERNAL FAILURE (Continued)

FIGURE I-7. GRAVITY DAM BEHAVIOR DURING AN EARTHQUAKE



FOUNDATION FAILURES

A seismic analysis must consider not only the effects of ground motions on the structure, but also their impact upon the strength of the foundation and abutments.

Two main types of foundation failure need to be considered:

- Deformation, settlement, and fault movement
- Liquefaction

I. OVERVIEW: MODES OF SEISMIC STABILITY FAILURE

Deformation, Settlement, And Fault Movement

The dynamic strength of bedding planes and shear zones in the foundation is usually lower than their static strength. During earthquakes, movements can occur along faults or other weak zones in the foundation and abutments. These movements can cause a variety of problems:

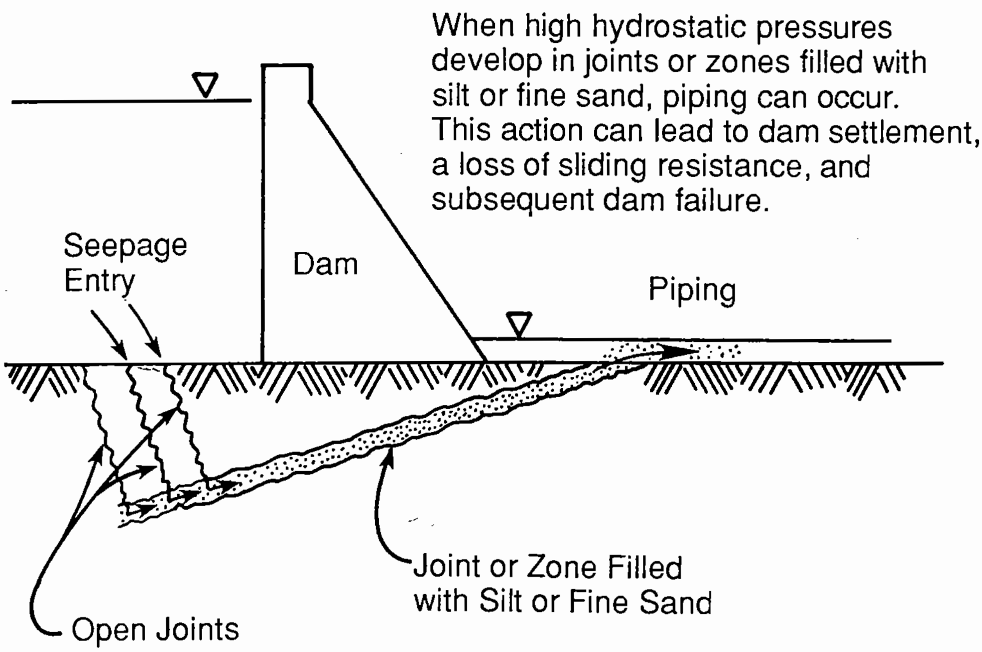
- Excessive movements can cause **tensile cracking** in the dam, which could possibly lead to dam failure.
- Excessive movements can open up faults and cracks in the foundation, which may result in increased seepage and a corresponding rapid **increase in uplift pressures.**
- Infiltration of water along bedding planes due to open cracks and fissures can cause **reduced foundation shear strength.** For gravity dams, the potential for sliding is greatest when the bedding planes are horizontal or they dip in the upstream direction.
- Infiltration of water along bedding planes can lead to **erosion of joint filler or shear zone material by piping.** This process can cause strength reduction as well as lead to large settlements or undermining of the dam. Figure I-8 depicts foundation piping.

Existing bedding planes or zones of weak material in the foundation should be analyzed using the expected post-earthquake strength parameters to determine sliding stability under normal loading conditions.

I. OVERVIEW: MODES OF SEISMIC STABILITY FAILURE

Deformation, Settlement, And Fault Movement (Continued)

FIGURE I-8. FOUNDATION PIPING



Liquefaction

Liquefaction is the sudden large decrease of the shearing resistance of a cohesionless soil. It is caused by the rapid, temporary increase of the pore water pressure due to cyclic loading, resulting in transformation of the material into a fluid mass.

This mode of failure most commonly occurs when the dam is founded on fine- to medium-grained saturated soils. Loose to medium dense sands have a risk of liquefaction under earthquakes with a peak ground acceleration of 0.1g or more. Most concrete dams are founded on rock and thus are not subject to liquefaction and collapse.

I. OVERVIEW: MODES OF SEISMIC STABILITY FAILURE

SECONDARY EVENTS

Secondary events such as overtopping may be caused by seismically induced surface waves, or seiche waves, in the reservoir or by landslides into the reservoir. Overtopping may cause erosion of the foundation at the toe of the structure. The erosion can result in loss of toe support or passive resistance and thus cause sliding failure. However, there have been no reported instances in which overtopping due to seismically induced seiche waves has led to this mode of failure.

I. OVERVIEW: SUMMARY

SUMMARY: STABILITY CONSIDERATIONS

Unit I described the impact of static and seismic instability on dam safety and gave an overview of modes of static and seismic stability failure.

Modes Of Static Failure

Static failure modes are outlined in Table I-2.

TABLE I-2. MODES OF STATIC FAILURE

Failure	Results From . . .
Sliding Failure	• Low foundation shear strength. • Bedding planes and joints containing weak material, such as clay or bentonite. • Seams of pervious material, if seepage through them is not controlled to prevent detrimental uplift. • Faults and shear zones.
Overturning Failure	• Insufficient weight or improper distribution of weight in the dam cross section to resist the applied forces. • Tensile cracking over portions of the base of the structure which is not in compression, resulting in high uplift forces and a loss of resistance to overturning. • Erosion of the rock foundation at the toe of the dam due to overtopping or rock deterioration. • High uplift pressures caused by inadequate seepage control or pressure relief. • Excessive hydrostatic pressures due to severe flood conditions, resulting in higher reservoir levels than the dam was designed to accommodate.

Concrete Deterioration And Concrete Distress

A dam's ability to resist sliding and overturning can be compromised by concrete deterioration and concrete distress.

Concrete deterioration is caused by:

- Environmental factors
- Chemical factors
- Defective or inferior concrete

Continued . . .

Concrete Deterioration And Concrete Distress (Continued)

Concrete distress includes:

- Cracking caused by excessive tensile or compressive stresses, high impact loads, or differential movements of foundation and abutment materials
- Cavitation
- Damage caused by earthquake, water surges, or equipment operation

Modes Of Seismic Failure

Seismic failure modes are summarized in Table I-3.

TABLE I-3. MODES OF SEISMIC FAILURE

Failure	Occurs When . . .
Internal Failure	• The ground motions of an earthquake subject a dam to dynamic loads that cause tensile stresses significantly higher than the static strength of the concrete. Tensile stresses cause cracking which can lead to failure if the reservoir cannot be contained long enough to take remedial action.
Foundation Failures	
• Deformation, settlement, and fault movement	• An earthquake causes movements along faults or other weak zones in the foundation or abutments. These movements can lead to tensile cracking in the dam, increased seepage and a corresponding rapid increase in uplift pressure, reduced foundation shear strength, or erosion of joint filler or shear zone material by piping.
• Liquefaction	• Cyclic loading causes a rapid, temporary increase of pore water pressure, which transforms cohesionless soil into a fluid mass. (Concrete dams founded on rock are not subject to this type of failure.)
• Secondary Events	• An earthquake causes seiche waves or landslides, which in turn cause a secondary event such as overtopping and erosion of the foundation at the toe of the structure. Sliding failure can result.

UNIT II

REVIEW AND EVALUATION OF PROJECT DATA

II. REVIEW AND EVALUATION OF PROJECT DATA: OVERVIEW

INTRODUCTION

Potential instability in a concrete dam may exhibit itself visibly with cracking, leaking, displacement, or other such types of deficiencies. However, because concrete dams can fail suddenly without visible warning, an evaluation of a dam's stability cannot rely solely on on-site inspections, but should include a review of project data, and in many cases additional investigations and analyses. This is especially true considering that most dams have not experienced maximum loading conditions.

Thus, evaluation of concrete dam stability usually involves two phases: review and evaluation of project data, and analysis. This unit describes the review and evaluation of project data (i.e., all pertinent available records, including the documentation of inspections and past operation).

Reviewing the design, construction, and operating records of a dam can help pinpoint areas of weakness or inadequacy, as well as check the current validity of assumptions regarding hydrologic and seismic loading.

II. REVIEW AND EVALUATION OF PROJECT DATA: DOCUMENTATION REVIEW

INTRODUCTION

A review of project data provides information related to the type of dam to be evaluated and its features, construction details, geologic setting, design assumptions, methods of analysis, instrumentation, monitoring, stability design measures, and construction materials.

The types of project data specific to concrete dams that should be reviewed and evaluated include:

- Hydrology
- Geology
- Structural analyses
- Instrumentation data
- Stability design measures that were incorporated into the dam

Reviewing this information will make it possible to identify conditions that may affect the safety of a dam and to identify any specific field investigations and data collection that may be necessary for analysis.

Data review also provides a basis for evaluating the adequacy of design factors of safety. Information that is obtained about as-built design and construction should be evaluated by comparing it to current practice and regulatory requirements.

Further information about where to find these data can be found in the TADS modules entitled Preparing To Conduct A Dam Safety Inspection and The Dam Safety Process.

HYDROLOGY

Hydrologic data should be reviewed for the following information:

- Assumptions regarding the magnitude of the design flood

- Normal reservoir and tailwater elevations

- Maximum reservoir and tailwater elevations expected

Current potential flood magnitudes may be different, and are often greater, than those assumed during design. Thus, reservoir loading on the dam may be more severe. The potential for overtopping may also exist and need to be evaluated.

This information will dictate the reservoir loading to be used in analyses.

II. REVIEW AND EVALUATION OF PROJECT DATA: DOCUMENTATION REVIEW

GEOLOGY

Earth materials behave in different ways, depending upon the conditions to which they are subjected. Some of the conditions imposed upon earth materials by a dam and reservoir that can affect a dam's stability are loading, unloading, saturation, and drying.

During the pre-design phase of a dam construction project, numerous site investigations are conducted to determine the geologic makeup of the dam site and surrounding area, and the results of those investigations are recorded. A review of data available on the site conditions will allow you to become familiar with the . . .

- Regional and site geology, including characteristics of foundation rock and soil,
- Geologic features of the dam foundation and abutments, and
- Relationship of the geologic features to the components of the dam.

You should evaluate the information to identify:

- Potential problematic materials in the foundation and/or abutments
- Areas of known or potential slides
- Any known faults in the foundation
- Areas susceptible to:
  - Subsidence or settlement (especially differential settlement)
  - Liquefaction
  - Uplift pressures

Records of site investigations may be found in the Dam Safety File. However, in the event that data on site conditions are not available, geologic information may be found by reviewing:

- Local and regional geologic maps, plans, and sections
- Soil survey reports
- Geological literature
- Well logs
- Aerial photographs of the site and vicinity
- Topographic maps
- Foundation treatment records
- Materials test records (soil, rock, water)
- Interviews with individuals knowledgeable about the area of the dam site

For more information on different types of earth materials and some of their engineering properties and deficiencies, see the TADS module entitled Inspection Of The Foundation, Abutments, And Reservoir Rim.

II. REVIEW AND EVALUATION OF PROJECT DATA: DOCUMENTATION REVIEW

STRUCTURAL ANALYSES

Structural analyses determine the required geometric proportions of the dam, required concrete properties, the various loads on the dam, and the support provided by the foundation and abutments. Information from structural analyses is used to proportion the dam so that it has the following qualities:

- Stability against sliding and overturning
- Ability to safely resist all anticipated loads without overstressing the concrete or foundation
- Resistance to deterioration or damage from environmental forces

Structural data should be reviewed for the following information:

- Geometric configuration of the dam:
  - Final dimensions as determined by structural analysis
  - Reasons for the dimensions used
- Materials used in the design of the dam:
  - Types and strengths of concrete and other materials assumed and used in design
  - Calculated maximum stresses on concrete and other materials used in the dam
- Loading conditions:
  - Assumed water, earth, and ice loads used in design
  - Critical load combinations analyzed
  - Calculated maximum stresses on foundation and abutments
- Foundation and abutments:
  - Assumed load carrying and shear transfer capacities of the foundation and abutments
  - Assumed uplift values, critical uplift areas, and areas treated for uplift pressures
- Methods of analysis used for stress calculations during static loading and seismic loading

II. REVIEW AND EVALUATION OF PROJECT DATA: INSTRUMENTATION DATA

INTRODUCTION

During the investigation, design, construction, and operating phases in the life of a dam, instruments may have been installed for two main reasons:

- Original instrumentation that was planned and installed for the purpose of monitoring general dam performance and verifying design assumptions, and
- Additional instrumentation installed during the construction or postconstruction periods to monitor specific problems.

INSTRUMENTATION DATA

You should review instrumentation records to determine if dam performance is commensurate with design assumptions, to become familiar with any known or suspected problems, and to identify any new performance problems. The following are examples of questions to consider in your review:

- What types of instruments were installed and where are they located?
- What performance factors (such as concrete degradation, dam movements, foundation settlement, seepage, or uplift pressures) are being monitored?
- Are there any anomalous data **not** attributable to instrument malfunction or reading and processing errors?
- Have any instruments become inoperable, and are they critical to monitoring dam performance?
- Are any known problems being monitored and what is their current status?
- Are there any conditions not presently monitored that should be?

All data from instrumentation should be plotted or presented in a meaningful manner and reviewed.

The specific types and locations of instruments are normally identified in the instrumentation plan and often are also shown on the design and/or as-built plans. The purpose of these instruments may sometimes be found in the designer's operating criteria or similar documentation.

Table II-1 lists the types of instruments that are commonly included and the data they typically measure. More detailed information regarding instrumentation is contained in the TADS module Instrumentation For Embankment And Concrete Dams.

Continued . . .

INSTRUMENTATION DATA (Continued)

TABLE II-1. INSTRUMENTATION FOR CONCRETE DAMS

Instruments	Typical Measured Data
Seepage weirs and flumes	Seepage/leakage
Piezometers	Seepage and uplift pressures
Observation wells	Seepage flow depths
Plumblines and pendulums	Vertical rotation of dam
Inclinometers	Deflection and rotation of dam, abutments, or reservoir rims
Strain meters or gauges	Movements of soil or structures
Extensometers	Movements of soil or structures
Stress meters or gauges	Pressures in soil or structures
Foundation deformeters or plates	Foundation movements
Seismographs	Earthquake shocks
Surface monuments	Movements in alignment or elevation
Thermometers	Temperatures and temperature changes
Electronic distance measuring instruments	Structure displacements
Whittemore strain gauges	Strains due to loads and temperature changes
Joint meters	Movement between monoliths

II. REVIEW AND EVALUATION OF PROJECT DATA: STABILITY DESIGN MEASURES

INTRODUCTION

Stability design measures are features included in the structure to ensure static and seismic stability of the dam. Conditions that may promote instability may relate to hydrology, the site geology, dam geometry, location and climate, construction materials, and construction methods. Stability design measures help to minimize or prevent the types of accidents and failures discussed in the previous sections.

STABILITY DESIGN MEASURES

In evaluating the stability of concrete dams, as well as reviewing and evaluating project data, it is helpful to understand what measures are commonly used to enhance static and seismic stability. This knowledge will make it possible to identify features of a dam that are important to stability and to understand the various remedial measures that can be taken to improve stability.

This section provides an overview of typical stability design measures. It includes information on the types of problems that are considered and the principal measures that may be applicable. These measures include:

- Ample freeboard
- Geometric configurations to reduce tensile stresses in the foundation and in mass concrete
- Treatments to strengthen foundation and abutment materials
- Reduction of uplift pressures and seepage by means of drainage, foundation grouting, or cutoffs
- Abutment and toe protection during overtopping
- Concrete strength and durability

Ample Freeboard

Freeboard is the distance between the stated water level and the top of the dam. Ample freeboard is required to ensure that the dam is not overstressed. Overtopping can lead to erosion of the foundation at the toe of the dam, with possible detrimental effects on sliding and overturning resistance. The designer must, at a minimum, meet applicable policies and regulations. Considerations for providing ample freeboard include:

- Wave setup from earthquake shaking, fault displacement in the reservoir, tilting of the reservoir, and landslides into the reservoir.

- Possible storms and/or snowmelt runoff into a frozen reservoir (thereby reducing possible storm water storage and routing).

- Capability of the outlet works to regulate the reservoir water surface in the event of unexpected or extreme conditions.

- Potential settlement of soil foundations or elastic compression of soft rock foundations.

II. REVIEW AND EVALUATION OF PROJECT DATA: STABILITY DESIGN MEASURES

Geometric Configurations To Reduce Tensile Stresses In Foundations

An analysis for overturning will determine if tensile stresses will occur on the base of a gravity or buttress dam during an earthquake. If excessive tensile stresses will occur, then additional compressive stresses must be applied to the base of the dam to offset this tension. This is usually done by adding weight to the dam or by anchoring the base of the dam to the foundation with tendons.

Arch dams do not usually require an analysis for overturning. These dams are normally analyzed as curved horizontal beams that transfer the reservoir load to the canyon walls.

To ensure that the entire base of an arch dam is in compression (that is, that no tension exists), good design practice dictates that the resultant force of all the loads must fall within the center one-third portion of the base.

Any area along the base of a dam that is not in compression is considered "cracked," and a cracked base analysis is performed. Such an analysis frequently requires that full uplift pressures (equal to the full reservoir head) be applied over the entire base of the dam that is not in compression. The analysis must also satisfy stability requirements.

Generally speaking, the most effective geometric shape to deal with potential tension in the foundation is a gravity section with a **vertical upstream face** and a **sloping downstream face,** with the slope adjusted to meet the overturning stability and foundation tension requirements. The base width of a gravity dam is usually from 70 to 90 percent of its height.

At sites where the cost of concrete is high, **buttresses** and possibly a **downstream apron** may be considered. Buttresses, however, are more difficult to design and construct than a gravity section, and they require a detailed structural analysis using reinforced concrete for the aprons, buttresses, and faces of the dam.

Geometric Configurations To Reduce Tensile Stresses In Mass Concrete

Tensile stresses in mass concrete are generally a result of one of the following:

- High internal temperature gradients, which occur particularly where there is an anomaly, discontinuity, or rapid change in geometry of the structure.
- Significant daily and seasonal changes in ambient temperatures.
- Load-induced stress concentrations at openings and abrupt changes in geometry, which produce secondary tensile and shear stresses.
- Unanticipated foundation or abutment movements.

II. REVIEW AND EVALUATION OF PROJECT DATA: STABILITY DESIGN MEASURES

Geometric Configurations To Reduce Tensile Stresses In Mass Concrete (Continued)

The following are some of the geometric configurations that can be used to reduce tensile stresses in concrete:

- Gradual changes in section thicknesses, or curved or transition sections used with large sections.
- Haunches or fillets used where smaller monolithic sections adjoin larger sections or in inside corners of rectangular openings.
- Curved shapes in gallery or tunnel roofs, gates, and other openings.
- Drains, galleries, and other openings located away from cold sources to keep the thermal gradient lower and reduce the potential for cracking.
- Properly designed expansion and contraction joints (including joint filler and joint sealer) where high differential temperatures are likely to cause high mass volumetric and/or linear changes in the concrete. Waterstops are used in joints to control seepage, and joint keys or steel dowels may be used to maintain alignment where differential movement across the joint is a concern.
- Proper geometric configuration to minimize or eliminate load-induced tensile stresses.

Treatments To Strengthen Foundation And Abutment Materials

The stability of a concrete dam also depends on the stability of the foundation and abutment materials. At times, it is necessary to treat rock so that it will be more capable of supporting the dam. Three of the most common types of treatments are:

- Smoothing the abutment areas
- Removal and replacement
- Rock reinforcements

Smoothing The Abutment Areas

Removing overhangs and smoothing sharp breaks in the slope between the foundation and abutments helps to relieve stress concentrations that can cause cracking in the dam after construction. These areas are smoothed and, if necessary, reinforced with grout.

Removal And Replacement

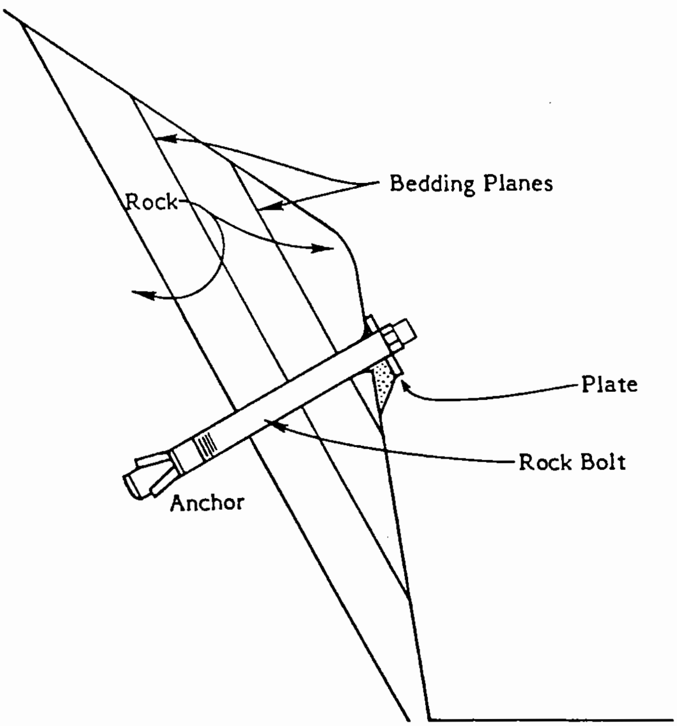
Overburden and weathered or badly fractured rock is removed to the competent rock formation. It may be replaced with concrete to smooth the area and provide a more stable foundation.

II. REVIEW AND EVALUATION OF PROJECT DATA: STABILITY DESIGN MEASURES

Rock Reinforcements

Rock reinforcements, such as rockbolts, anchors, and tendons, stabilize slopes and increase the overall strength of abutments and adjacent areas. Rockbolts, anchors, and tendons are steel rods or cables that are inserted through unstable rock or even structures to reinforce and anchor the unstable element to a stable mass. Figure II-1 illustrates how a rockbolt holds together unstable masses of rock.

FIGURE II-1. ROCKBOLT



Reduction Of Uplift Pressures And Seepage

Uplift pressures and seepage may be reduced by means of drainage systems, foundation grouting, and cutoffs.

Drainage Systems

Leakage and seepage occur in all concrete dams. The amount of flow is a function of the reservoir level, water tightness of joints and lifts, extent of cracking, foundation permeability, reservoir and ambient temperatures, and grout curtain or cutoff effectiveness. As the level of the reservoir rises, the flow rate generally increases. As the temperature drops, the concrete contracts, allowing joints or cracks to open, and the flow rate usually increases.

Continued . . .

II. REVIEW AND EVALUATION OF PROJECT DATA: STABILITY DESIGN MEASURES

Drainage Systems (Continued)

Drainage systems designed to intercept and carry away leaking and seeping water are provided in concrete dams to serve several purposes:

- To control and direct seepage to desired areas in order to prevent leaching of concrete, unsightly conditions, and maintenance or operation problems.
- To reduce uplift pressures that may cause instability.
- To reduce seepage exit gradients that may cause piping and internal erosion in foundations and abutments.

The design of a drainage system may include various drainage features that contribute to the stability of the dam, such as formed drains, drainage gutters, and foundation drains.

Grouting Of Foundations And Abutments

Two main types of grouting are done in association with concrete dams: surface grouting (commonly called dental grouting) and injected pressure grouting.

Dental grouting involves brooming grout slurry into cracks and small voids. It is normally performed on rough surfaces of broken, fractured, and weathered rock. Dental grouting is used to achieve the following purposes:

- To provide a smooth, regular surface for the placement of concrete.
- To provide a barrier to the vertical movement of soils and water across the interface of the dam and foundation and abutments.
- To seal surface cracks and voids to prevent seepage along the interface from eroding the foundation.

Pressure grouting involves injecting grout (cement, bentonite, or chemical gels) into deeper pervious zones of fractured rock. Pressure grouting is used:

- To reduce the quantity of seepage flow through the foundation or abutments.
- To reduce seepage pressures downstream from the grouting.
- To fill voids.

Continued . . .

II. REVIEW AND EVALUATION OF PROJECT DATA: STABILITY DESIGN MEASURES

Grouting Of Foundations And Abutments (Continued)

Generally speaking, the grout is pressure-injected into a line of drilled holes at a predetermined spacing parallel to the centerline of the dam, forming a "grout curtain." The effectiveness of grout curtains in **reducing seepage quantities** varies considerably and depends on such factors as:

- Success in reaching a deeper, more impervious material in the foundation.
- Porosity and continuity of voids, fractures, or joints in the foundation.
- Lateral penetration of the grout.
- Number and sizes of "windows" of incomplete grouting in the grout curtain.

Locating the grout curtain near the upstream portion of the foundation helps in **reducing uplift pressures** across a greater portion of the foundation. However, it is difficult to reduce uplift pressures successfully by grouting because even small windows in the curtain will allow pressure to be transmitted throughout a saturated foundation, even if the quantity of seepage flow is fairly small. Under these conditions, seepage and uplift pressures through the foundation respond very quickly to changes in reservoir elevations.

For this reason, grout curtains alone are usually not relied on for reducing uplift pressures. Rather, a grout curtain is commonly used in conjunction with adequate drainage systems.

Cutoff Measures

Grout curtains are only one type of cutoff measure that may be used to reduce seepage and uplift pressures. Others include concrete cutoff walls, sheet pile cutoff walls, bentonite slurry trenches, earth-filled cutoff trenches, and reservoir and abutment blankets.

Concrete cutoff walls can be installed to considerable depths in earth foundations and in pervious rock using current technology. Concrete cutoffs can normally be assumed to be completely impervious throughout their depth when making a seepage or uplift analysis. Other types of cutoffs, such as **sheet pile walls, bentonite slurry trenches,** and **earth-filled trenches,** are used in earth foundations. Thus they are more commonly used with embankment dams or occasionally with concrete dams of low to moderate height.

Blankets of compacted earth are often used to extend the seepage entrance point further upstream from the base of the dam. By distributing the hydraulic pressure losses over a longer length, the blanket reduces seepage quantities and uplift pressures under the dam.

Reservoir and abutment blankets can effectively reduce seepage quantities and uplift pressures when relatively impervious materials are used and the layout is designed according to detailed geologic data. Blankets can be damaged by erosion and wave action if not protected. Additional seepage control measures such as foundation drains are usually provided when impervious blankets are used.

II. REVIEW AND EVALUATION OF PROJECT DATA: STABILITY DESIGN MEASURES

Abutment And Toe Protection During Overtopping

The effects of damage to the abutments and toe of a dam during overtopping can range from minor, requiring only local repairs, to catastrophic, causing major damage and failure. Where abutments and toes are weak, a serious concern is that overtopping will cause deep scour and removal of rock and soil. This can result in such problems as:

- Shortened seepage paths resulting in increased seepage and possibly piping and internal erosion.
- Removal of material at or under the toe, which reduces resistance to sliding or overturning.

In designing protective measures, designers consider the probability and frequency of overtopping, the potential hazard and downstream damage, and the type and condition of materials to be protected. Rock and soil foundations usually require different measures.

Rock Foundations

Where rock exists but is not sufficiently hard or massive to resist the impact of overtopping, or where the rock is subject to deterioration by weathering, defensive measures may include shotcrete, dental concrete, pressure grouting, concrete aprons, and anchor rods. The selection of treatment depends on the type of rock; the size, spacing, openness, and depth of fractures, joints, and weathering; and the impact and duration of overtopping.

Soft Bedrock And Soil Foundations

Where the foundation and abutments consist of soft or highly fractured and weathered bedrock and soil, the abutments and toe may be protected with wire-pinned rock, heavy rock riprap, or grouted rock riprap.

Concrete Strength And Durability

Concrete strength is a product of proper design and control of concrete mix, manufacture, and placement. Concrete may also be reinforced (although this is generally impractical for concrete gravity dams) to deal with tensile, compressive, and shear stresses from structural and other loadings. Strength is important for concrete durability.

Concrete durability is generally defined as resistance to the environment to which the concrete is exposed. Environmental forces include:

- Freezing and thawing
- Wetting and drying
- Chemicals
- Abrasion
- Hydraulic forces
- Heat of hydration

II. REVIEW AND EVALUATION OF PROJECT DATA: STABILITY DESIGN MEASURES

Concrete Mix And Placement

The following methods are used to improve the ability of concrete to resist the specified environmental forces.

- **Freezing And Thawing.** Resistance to damage by freezing and thawing is greatly improved by:
  - Presence of entrained air
  - Adequate concrete strength, achieved through controlled maximum water-cement ratio and quality control of ingredients

- **Wetting And Drying.** Resistance to damage by wetting and drying can be improved through:
  - Use of low maximum water-cement ratios to reduce permeability
  - Thorough vibration of concrete
  - Uniform mixing

- **Chemicals.** Resistance to chemical damage can be improved by several methods:
  - Use of sulphate-resistant cements
  - Use of low-alkali and sulphate-resistant aggregates
  - Use of low maximum water-cement ratios
  - Thorough mixing and vibration

- **Abrasion.** Resistance to damage by abrasion can be improved by increasing concrete strength and using large, hard aggregate.

- **Hydraulic Forces.** Resistance to damage by hydraulic cavitation and erosion forces can be improved by:
  - Use of pozzolan additives and wood float finishing to improve workability, provide smooth finishes, and eliminate pits and rough edges
  - Use of low maximum water-cement ratios to improve concrete strength
  - Use of 1-1/2-inch maximum size aggregate within the upper 1 to 2 feet of finished surfaces, to provide a dense, cavitation-resistant surface
  - Careful finishing and detailing of all joints to ensure that opposing edges are flush with each other

- **Heat Of Hydration.** Thermal strains are induced by the heat generated by the hydrating cement during construction. The following techniques are used to control temperatures within acceptable limits:
  - Use of low cement contents for mass concrete
  - Use of cements with low heat of hydration
  - Use of pozzolan in place of a portion of the Portland cement, or use of a blended hydraulic cement
  - Control of lift thicknesses and/or placing intervals
  - Control of maximum placing temperatures
  - Postplacement cooling by embedded cooling pipes
  - Insulation of concrete surfaces to prevent temperature differentials
  - Precooling of mix ingredients

Continued . . .

Concrete Mix And Placement (Continued)

For specific guidelines and requirements related to these methods, consult agency policy, criteria, and other technical publications. Industry practice codes and publications also contain detailed recommendations on this subject. Publications of the American Concrete Institute and the Portland Cement Association and the Bureau of Reclamation's Concrete Manual are examples of useful references.

Reinforcement

Concrete is strong in compression and shear, but weak in tension. Therefore, steel reinforcement is often used to carry the tensile stress in structural members, such as walls, columns, slabs, and footings. Buttress dams often require reinforcement in all their structural members. In gravity and arch dams, reinforcement is generally not provided. Spillway walls, inlet towers, parapets, and other appurtenances require detailed structural analysis to determine reinforcement requirements.

Tension stresses in concrete dams and structural members may have numerous sources, such as:

- Structural loadings
- Restrained volume changes due to temperature and shrinkage
- Secondary stresses
- Differential movements

Reinforcement, jointing, and various other measures are used to deal with such stresses.

Structural Loadings. Loadings will cause bending and shear in structural members. If unreinforced, these structural members can develop tension-induced cracks, which spread from the tension face of the member toward the compression face until failure results.

Restrained Volume Change. Concrete expands and contracts as it heats and cools. If expansion or contraction is inhibited by confinement or restraint of the concrete, compressive or tensile stresses may develop and cause cracking or spalling of the concrete. In small structural elements, the cracks may spread through the entire element. In massive structures, cracks are usually widest at the surface and diminish with depth. However, in some cases the cracks may spread through an entire monolith.

Measures used to deal with these stresses include temperature and shrinkage reinforcement and expansion and contraction joints.

Secondary Stresses. Secondary stresses occur where there are anomalies or sudden changes in geometry, such as at inside corners of rectangular openings; at openings in walls, aprons, or beams; or where smaller structural elements are monolithic with larger concrete masses. Secondary stresses alone or in combination with other forces can cause cracking or spalling.

Various types of concrete, steel reinforcement, and geometric forms such as fillets are used to deal with secondary stresses.

Continued . . .

II. REVIEW AND EVALUATION OF PROJECT DATA: STABILITY DESIGN MEASURES

Reinforcement (Continued)

Differential Movements. Stresses caused by differential movements can take any form, depending on the nature, direction, and amount of movement. This problem is commonly dealt with by means of foundation or abutment treatment before the dam is constructed. Other methods include use of reinforced concrete members to prevent settlement cracking by bridging weak areas of the foundation, and use of reinforcement to provide shear transfer across potential settlement cracks.

SUMMARY: REVIEW AND EVALUATION OF PROJECT DATA

Unit II described the types of documents and instrumentation data to review in order to prepare to evaluate the stability of a concrete dam.

Unit II also described design measures used to help prevent static and seismic instability. These measures include:

- Ample freeboard
- Geometric configurations to reduce tensile stresses in foundation
- Geometric configurations to reduce tensile stresses in mass concrete
- Treatments to strengthen foundation and abutment materials
- Reduction of uplift pressures and seepage, through:
  - Drainage systems
  - Grouting of foundations and abutments
  - Cutoff measures
- Abutment and toe protection during overtopping
- Concrete strength and durability

UNIT III

ANALYSIS CONSIDERATIONS

III. ANALYSIS CONSIDERATIONS: OVERVIEW

INTRODUCTION

Data obtained through review of project data, exploration, testing, and evaluation are used in conducting static and seismic stability analyses. A variety of analytical techniques may be used, depending on the type of structure, site conditions, loading conditions, and other variables.

This unit describes the kinds of information required for a stability analysis and the exploration and testing that may take place. The person who reviews project data and conducts the investigation and data collection may gather data for the analyses, or may recommend that certain analyses be considered. The actual analyses are normally carried out by qualified engineering specialists.

III. ANALYSIS CONSIDERATIONS: INFORMATION NEEDED FOR ANALYSIS

INTRODUCTION

In order to plan for a stability analysis, you must be familiar with the types of information required to perform a stability analysis and determine if the available information is adequate. The following types of data are required:

- Configuration of the dam as it was designed and as it was constructed
- Physical properties of the concrete
- Geotechnical features of the dam site
- Material strengths during seismic loading
- Actual uplift pressures within the dam and foundation
- Loads that the dam may experience during its lifetime

CONFIGURATION OF THE DAM

The configuration of the dam should be obtained from the as-built drawings when possible. As-built drawings may show changes that were made in the original configuration because field conditions, foundation excavations, and foundation treatments differed from those indicated in the original design documents.

The type of transverse contraction joints used in a dam are important in stability analyses. If the joints are keyed, the dam becomes partially monolithic and has the ability to transfer shear from one monolith to the next. Thus, keys improve stability by helping to transfer horizontal loads from the center of the dam toward the abutments. Keys also help in the transfer of vertical load and allow the dam to bridge over weak areas in the foundation. They do not, however, allow the transfer of tensile stresses.

CONCRETE PROPERTIES

Physical properties of the existing concrete may differ from those assumed for design of the dam. It may be advisable to have core samples taken for laboratory testing to confirm design and construction information. Testing existing concrete is especially important when a field inspection of the dam indicates that the concrete has deteriorated. Additional types of testing procedures are discussed in the TADS inspection module Identification Of Material Deficiencies.

III. ANALYSIS CONSIDERATIONS: INFORMATION NEEDED FOR ANALYSIS

GEOTECHNICAL FEATURES OF THE DAM SITE

The stability of the dam depends on the ability of the foundation to support it. It may be necessary to conduct extensive exploration, geologic mapping, and sampling and testing to obtain sufficient data about the condition of the foundation. Such studies can be used to identify potential failure planes in the foundation and to determine the strength and deformation characteristics of the materials along these failure planes. The data required for stability analyses include:

- Physical properties of the various foundation materials
- Physical geometry of all formations and deposits
- Dip and strike of the faults, shears, planes, and joints
- Shearing and sliding strengths of the discontinuities and the rock

Material Properties

Results of foundation exploration and testing should be available for an existing dam. If not, a testing program should be developed to determine the material properties of the foundation and the concrete-rock interface. Material properties that need to be established include shear strength, bearing capacity, modulus of elasticity, and Poisson's ratio.

Potential Failure Planes

Although the material properties of the foundation may be acceptable, the foundation may have areas of weakness that will affect stability of the dam. These areas may be planes or zones of inferior rock in the foundation or abutments. Extensive geologic mapping showing joint orientations, dips, and other features within the foundation is required to identify potential failure planes.

Shear failure along the potential failure planes can often occur through progressive failure, by which the maximum shear strength is not mobilized simultaneously along the entire failure surface. In addition, material along a joint may be presheared and altered in such a way that residual rather than peak shear strengths should be considered for the stability analysis.

Material Strengths

Shear resistance within the foundation depends on cohesion and internal friction of the rock. Shear resistance at the base of the dam depends on the cohesion and friction between the concrete and rock. The weakest plane, or potential failure plane, may consist of several different materials. These materials may be intact or fractured. Intact rock reaches its maximum strength with less deformation than fractured rock. Therefore, the peak shear strengths of each material are not directly additive. If the intact rock shears, the shear resistance of the plane is reduced to the frictional resistance for all materials along the plane. The shear resistance versus normal load relationship for each material along the potential sliding plane should be determined by testing whenever possible.

III. ANALYSIS CONSIDERATIONS: INFORMATION NEEDED FOR ANALYSIS

MATERIAL STRENGTHS DURING SEISMIC LOADING

Concrete

The apparent compressive and tensile strengths of concrete vary with the rate of loading during testing. As the rate of loading increases, compressive and tensile strengths also increase. Therefore, the properties of concrete under dynamic loadings, such as those present during an earthquake, are greater than under static conditions.

Foundation

The mobilized strength of soil foundations during cyclic loadings (earthquake) depends on several variables. This strength should not be generalized on without site-specific in situ data, laboratory testing, and evaluation by appropriate specialists. For example, clean, coarse-grained soils of moderate density will often densify further and gain strength during cyclic loading. If their permeabilities are high enough to dissipate the excess pore pressures, they will even gain an artificial, temporary strength when saturated. These temporary strength gains are not usually relied upon for stability analyses for cyclic loading conditions.

On the other hand, loose to moderately dense silts and sands build up excess pore pressures during cyclic loading. Because of the soil's limited permeability, the excess pressures cannot be rapidly relieved, and there is a very rapid loss of strength. Since most concrete dams are founded on rock, they are not subject to these types of gains and losses of strength during cyclic loading.

UPLIFT PRESSURES

Modern dams are designed assuming full uplift over 100 percent of the base area. Some older dams were designed assuming that full uplift acted over only a percentage of the base area, and this assumption has been found to be in error. However, many dams designed under the older criteria have performed satisfactorily, for several reasons:

- Pressure levels may be less than assumed in the original design because of good drainage or impermeability of the foundation.
- It takes many years to saturate concrete and dense foundation rock.
- The reservoir may be at full pool conditions only for short periods.
- The fact that the resultant falls outside the middle one-third of the base may not mean the dam is unstable.

Continued . . .

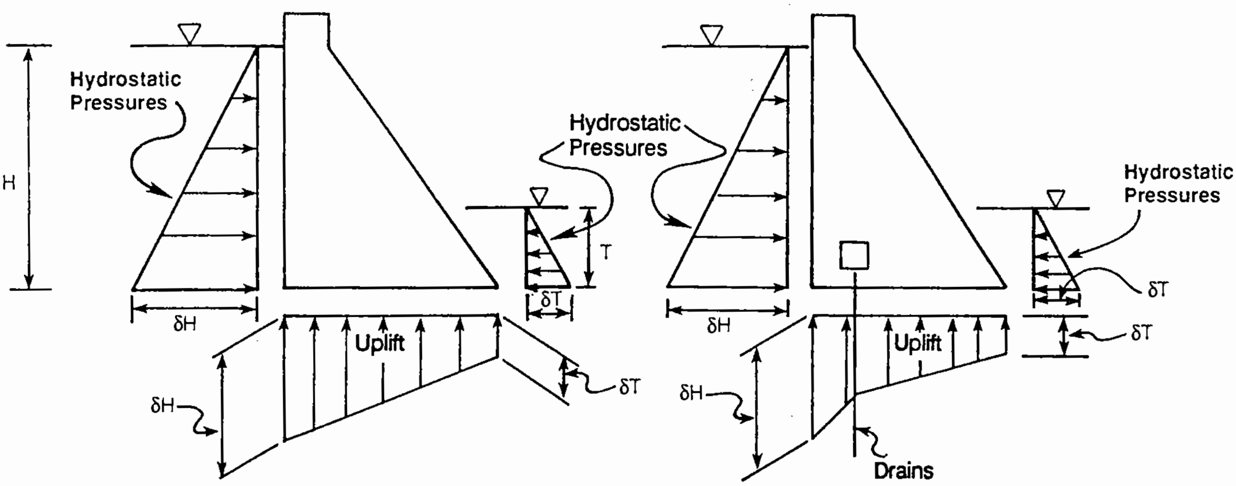
III. ANALYSIS CONSIDERATIONS: INFORMATION NEEDED FOR ANALYSIS

UPLIFT PRESSURES (Continued)

The design uplift assumptions are illustrated in Figure III-1. Actual uplift can also be greater than assumed uplift pressures, as shown in Figure III-2. Before measured rather than assumed uplift pressures are used in stability analyses, you must verify that:

- There are sufficient uplift data to ensure that the uplift (magnitude and distribution) used in the stability analysis is representative of actual conditions for both the long and short term.
- High hydrostatic pressures are not present in rock zones below the dam.
- The instrumentation is functioning properly.

FIGURE III-1. DESIGN UPLIFT PRESSURES



(A) WITHOUT DRAINS

Without drains, uplift pressure varies from headwater pressure to tailwater pressure as shown.

H = Headwater reservoir depth T = Tailwater reservoir depth UD = Uplift pressure at drain location δ = Unit weight of water

(B) WITH DRAINS

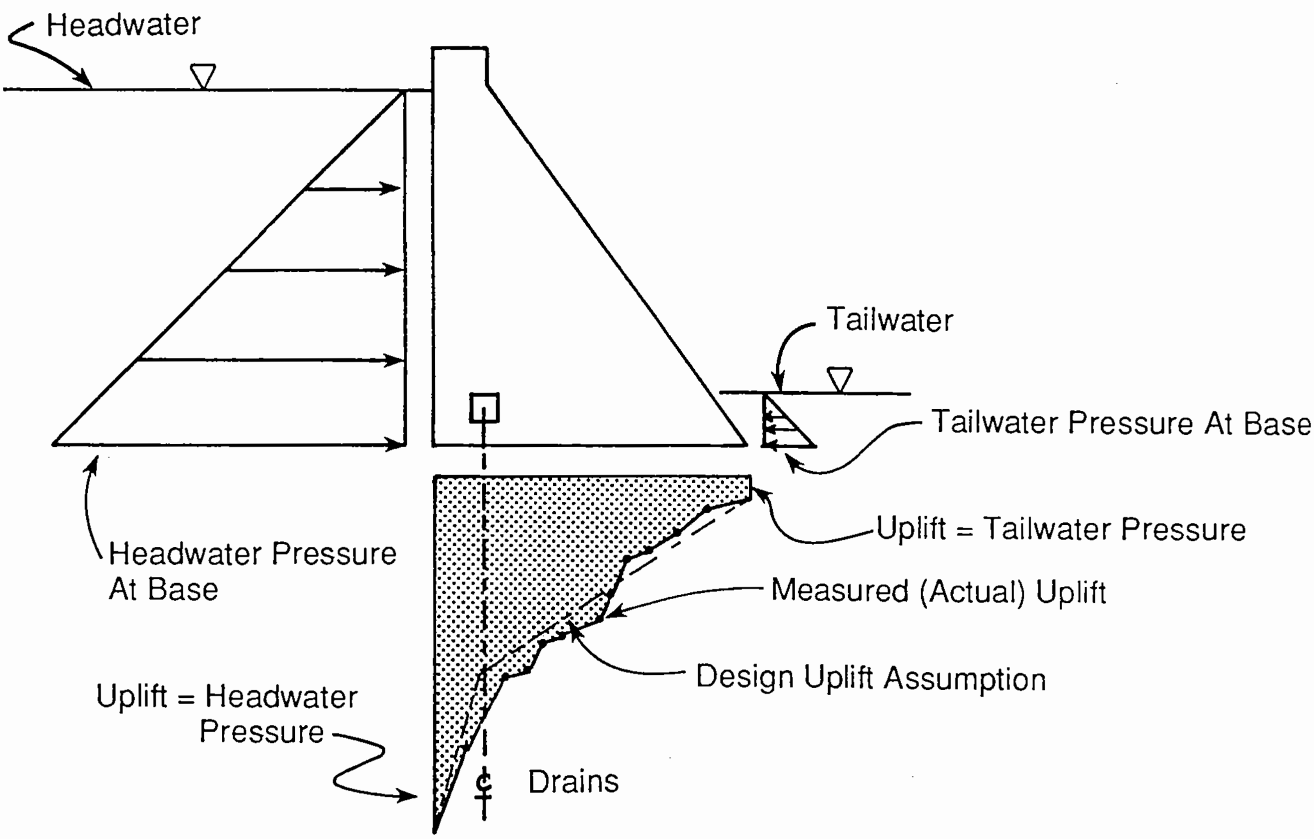
With drains, uplift pressure at the drain line is reduced to a value equal to:

$$UD = \delta T + \frac{(\delta H - \delta T)}{3}$$

Continued . . .

UPLIFT PRESSURES (Continued)

FIGURE III-2. DESIGN VERSUS MEASURED UPLIFT



LOADING CONDITIONS

Stability investigations are based on the most adverse combination of probable loading conditions. Only loading conditions that have a reasonable probability of occurring simultaneously should be considered for design and analysis. Figure III-3 illustrates the types of loads considered in dam design and analysis.

The following usual, unusual, and extreme loading combinations may be considered in the design and analysis of concrete dams:

Usual loading combination:

- Normal reservoir elevation--highest elevation at which water is normally stored, or the top capacity allocated to multipurpose use (for example, flood control, recreation, and conservation)
- Appropriate dead loads, uplift, sediment, ice, and tailwater
- Minimum usual temperatures (if applicable)

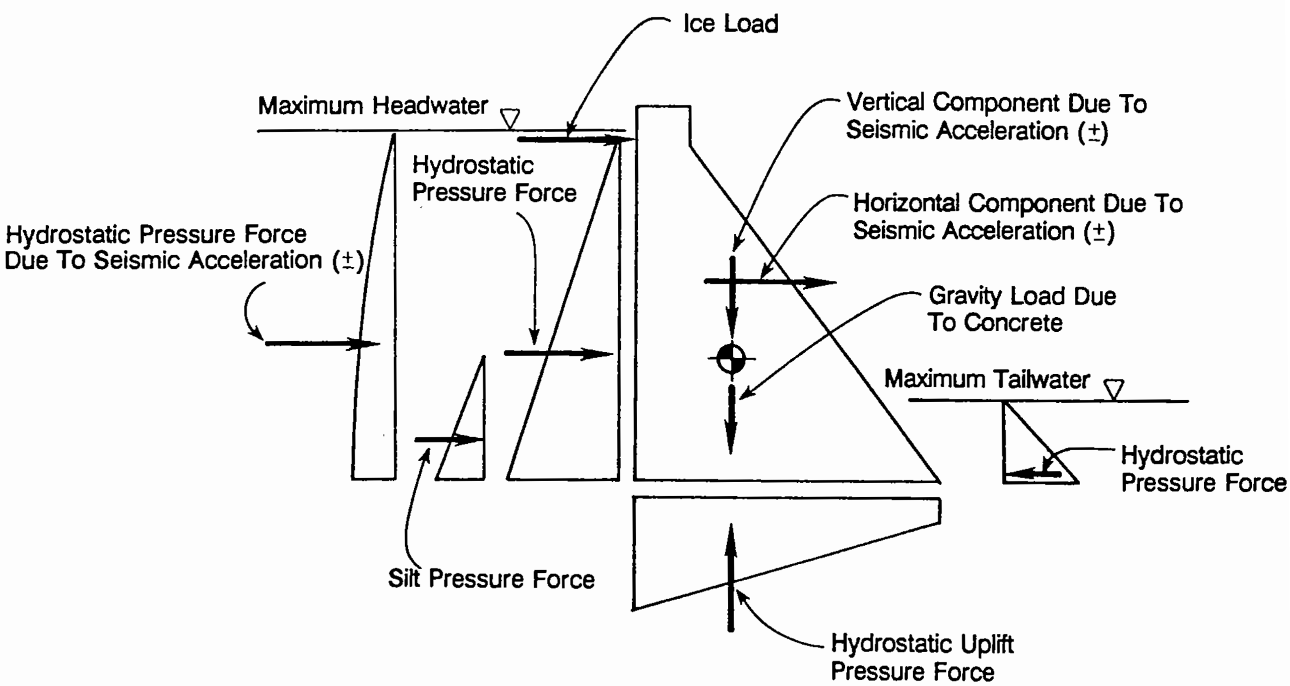
Continued . . .

III. ANALYSIS CONSIDERATIONS: INFORMATION NEEDED FOR ANALYSIS

LOADING CONDITIONS (Continued)

- **Unusual loading combination:**
  - Maximum reservoir elevation--highest anticipated water surface elevation
  - Other usual loads
- **Extreme loading combination:**
  - Maximum credible earthquake
  - Other usual loads

FIGURE III-3. RESULTANT FORCES ACTING ON A DAM



III. ANALYSIS CONSIDERATIONS: EXPLORATION AND TESTING

INTRODUCTION

Exploration and testing may be predetermined to be a necessary part of investigation, or they may be recommended in the site evaluation report. In either event, these activities provide data for the same purposes as instrumentation data: to identify causes of known deficiencies, to evaluate potential deficiencies, and to design remedial measures. Consultation with an engineering specialist at this point is important.

EXPLORATION AND TESTING

When considering additional exploration and testing, you should identify the intended use of data that will be obtained, to be certain that the following conditions are met:

- Samples of the proper type and size are obtained.
- Samples are collected in the proper locations.
- Appropriate data are logged.
- Appropriate tests are requested.

Additional testing may include laboratory testing and in-place field testing.

Laboratory Testing

Table III-1 lists some of the laboratory tests that may be requested, the purposes of the tests, and the kinds of samples needed.

Continued . . .

Laboratory Testing (Continued)

TABLE III-1. SELECTED LABORATORY TESTING FOR CONCRETE DAM INVESTIGATIONS

Test	Purpose Of Test	Type Of Sample* U	D
GEOTECHNICAL			
Shear testing	Analyzing stability of foundations, abutments, and reservoir slopes	X	
Consolidation testing	Analyzing settlement of foundations and abutments	X	
Permeability testing	Analyzing seepage in foundations and abutments	X	
Gradation analysis	Confirming gradation of required drainfills		X
Classification	Correlating borings and undisturbed sample testing		X
Chemical testing	Identifying aggressive or detrimental chemicals (sodium sulphates, acids, dispersive soils)		X
Resistivity/pH testing	Identifying corrosion potential		X
CONCRETE			
Compressive strength and density testing	Evaluating in-place compressive core samples	X	
Tensile testing	Evaluating in-place tensile strengths in core samples	X	

* U = Undisturbed; D = Disturbed

Continued . . .

Laboratory Testing (Continued)

TABLE III-1. SELECTED LABORATORY TESTING FOR CONCRETE DAM INVESTIGATIONS
(Continued)

Test	Purpose Of Test	Type Of Sample* U	D
CONCRETE (Continued)			
Shear testing	Evaluating in-place tensile strengths	X	
Modulus of elasticity	Evaluating in-place moduli of elasticity (static and dynamic)	X	
Poisson's ratio	Evaluating the in-place Poisson's ratio	X	
Aggregate testing	Testing size, gradation, hardness, durability, reactivity, impurities		X
Chemical analysis	Identifying chemical content of cement mortar constituents, impurities, undesirable chemical reactions		X
Density, permeability testing	In-place density, permeability, and freeze-thaw testing	X	

* U = Undisturbed; D = Disturbed

In-Place Testing

In addition to laboratory testing, the following types of in-place testing may be appropriate:

- Geotechnical:
  - In-place density testing
  - In-place permeability testing
  - In-place bearing capacity or strength testing
  - Various moduli
- Concrete
  - In-place soundness testing with Swedish hammers
  - In-place testing for reinforcing steel locations and cover
  - Various moduli

SUMMARY: ANALYSIS CONSIDERATIONS

Unit III described analysis considerations when evaluating the stability of a concrete dam.

Information Needed For Stability Analysis

The information needed to analyze static and seismic stability includes:

- Configuration of the dam as it was designed and as it was constructed
- Physical properties of the concrete
- Geotechnical features of the dam site
  - Material properties
  - Potential failure planes
  - Material strengths
- Material strengths during seismic loading
  - Concrete strength
  - Foundation strength
- Actual uplift pressures within the dam and foundation
- Loads that the dam may experience during its lifetime

Exploration And Testing

Unit III also described what types of exploration and testing might be conducted to further evaluate the stability of a concrete dam. Laboratory tests that might be requested in a site evaluation report were summarized in Table III-1. In-place testing includes geotechnical testing and concrete testing.

UNIT IV

STATIC STABILITY

IV. STATIC STABILITY: OVERVIEW

INTRODUCTION

This unit focuses on the static stability of concrete gravity dams, looking first at the basic stability requirements that gravity dams must meet and representative factors of safety that are used when determining a dam's allowable stresses.

Next the unit describes various methods used to analyze static stability and determine stresses in a dam. Some of the criteria considered when selecting a given analytical method are presented.

Finally, the use of computer programs in static stability analysis is discussed and several of the software programs that can be used to do analyses are presented. It is emphasized that the user must understand the assumptions and procedures of whatever analysis is selected.

IV. STATIC STABILITY: ANALYTICAL METHODS

INTRODUCTION

The following methods are commonly used to analyze static stability and determine stresses in the dam:

- Gravity Method
- Trial-Load Method
- Two- and Three-Dimensional Finite Element Methods
- Limit Equilibrium Method
- Cracked Base Analysis

A given analytical method is selected on the basis of regulatory requirements, the nature of known or suspected deficiencies, the type and configuration of the dam, and the failure mode being investigated (sliding, overturning, or overstressing). The gravity method is commonly used and in many cases is sufficient for analyzing most concrete dams. However, more sophisticated methods may be required for curved-in-plan structures or those with unusual configurations, and for conducting detailed static stress analyses and seismic stress analyses.

BASIC STABILITY CRITERIA

A gravity dam must meet the following basic stability requirements:

- **The dam must be safe against overturning at any horizontal plane within the dam, at the base, or on any weak plane or seam in the foundation.** To meet this standard, the allowable unit stresses established for the concrete and foundation materials must not be exceeded, and equilibrium of forces must be maintained. Allowable stresses are determined by dividing ultimate strengths of the materials by the appropriate factors of safety, similar to those listed in Table IV-1.

- **The dam must be safe against sliding on any horizontal plane within the dam, at the base, or on any weak plane or seam in the foundation.**

Specific stability criteria and factors of safety for a particular loading combination depend upon the type of analysis being done (for example, a foundation analysis vs. a structure or concrete analysis), the degree of understanding of the foundation/structure interaction and site geology, the variability and reliability of the foundation properties and strength, and to some extent the method of analysis.

For existing dams, assumptions used in the analysis are based upon construction records and the performance of the structure under historical loads. In the absence of available design data and records, investigations are conducted to verify all assumptions. The conservatism required depends on the quality and adequacy of the information available for use in the analysis.

Continued . . .

BASIC STABILITY CRITERIA (Continued)

TABLE IV-1. FACTORS OF SAFETY

Loading Condition	Factor Of Safety
For Dams With High Or Significant Hazard Potential:	
Usual	3.0
Unusual	2.0
Extreme	Greater than 1.0
For Dams With Low Hazard Potential:	
Usual	2.0
Unusual	1.25
Extreme	Greater than 1.0

Notes:

Factors of safety are commonly applied to the ultimate strength of the concrete and foundation materials to obtain allowable stresses for design. Allowable shear, tensile, and compressive stresses are determined in this manner. Factors of safety are also applied to sliding resistance (shear friction factor of safety) to determine if a dam can safely resist the applied loads.

Factors of safety are generally not used to evaluate overturning stability. Overturning resistance is considered to be adequate when the resultant of all the applied loads falls within the middle one-third of the base (when there is no potential for cracking at the dam-foundation interface). This requirement, however, is often relaxed for extreme loading conditions.

Tensile Stresses

The tensile capacity of concrete is approximately 10 to 15 percent of the compressive strength of the concrete. The tensile strength of horizontal lift joints within the dam will be somewhat low and may even be zero if no bond exists at the joint. Core drilling through the joint may be required to determine the actual tensile strength that can be developed across the joint.

Often in the original design, no tension is allowed at the rock/concrete interface assuming the tensile strength of this interface is zero. This assumption is conservatively made because it is recognized that there may already be fractures in the foundation just below this interface.

IV. STATIC STABILITY: ANALYTICAL METHODS

Importance Of Expert Advice

Failure to meet minimum factors of safety using the analysis procedures for proposed dams does not necessarily mean that dam rehabilitation or dam strengthening is required. Safety factors themselves are judgmental and depend not only on the probability of the design loads occurring during the life of the project, but also on the reliability and extent of the foundation and materials investigations. In addition, actual loads may differ from those used for design.

The converse is also true. In other words, a dam that meets established factors of safety may not be safe if these factors were based on a poor foundation and materials investigation or on inaccurate load and uplift assumptions.

Therefore,

> **Conclusions regarding the safety of an existing dam should be reached only after obtaining expert advice regarding the appropriate strength parameters, loads, analysis procedures, and additional explorations and testing required to conduct a stability analysis that represents actual conditions.**

GRAVITY METHOD

The gravity method of stress and stability analysis is used for the following purposes:

- Preliminary studies of gravity dams, depending on the phase of evaluation and the information required.
- Final evaluation of straight gravity dams in which the transverse contraction joints are neither keyed nor grouted.

Using the gravity method and elementary beam theory, the stresses in a cross section of a gravity dam can be determined. The gravity method is applicable to gravity sections with a vertical upstream face and a constant downstream slope and to those with a variable slope on either or both faces.

Use of the gravity method requires that the following simplifying assumptions be made about loads on the dam and the structural behavior of the dam:

- The concrete in the dam is a homogeneous, isotropic, and uniformly elastic material.
- The dam acts as a rigid body with respect to the dam foundation interface.
- All loads are transmitted to the foundation through cantilever action of the dam without support from adjacent monoliths.
- Stresses are distributed in a linear manner on horizontal planes.

Continued . . .

GRAVITY METHOD (Continued)

When using the gravity method, foundation stresses and factors of safety are determined. The stability factor of safety for sliding is often determined using the limit equilibrium method of analysis. Uplift is considered to reduce the normal force on the shear plane and thereby reduce frictional sliding resistance. In general, the minimum factors of safety that were shown in Table IV-1 apply.

Stability against overturning is usually determined by calculating the location of the resultant of all forces acting on the dam and by determining interface and foundation stresses. Uplift may or may not be present. Therefore, foundation bearing pressures are evaluated for both possibilities.

TRIAL-LOAD METHOD

A gravity dam may be made of a series of vertically cantilevered elements from abutment to abutment. If the cross-canyon profile is narrow with steep sloping walls, then adjacent cantilevered elements will be of different lengths. The loads applied from the reservoir will cause the longer elements to deflect more than the shorter elements.

If the transverse contraction joints in the dam are keyed, the movement of each cantilever will be restrained by the adjacent element. This interaction between adjacent elements will cause a twisting of the element and torsional moments. This condition changes the stress distribution from that of ordinary two-dimensional gravity analysis, in which the effects of torsion of the elements and deformation of the foundation are neglected. A three-dimensional analysis should be considered for gravity dams with keyed contraction joints and a sloping foundation. In general, a dam with keys is more stable than the same dam without keys because of the keyed dam's ability to transmit loads to the abutments.

If the adjacent elements are of the same length and on a relatively flat foundation, then torsional stresses are usually negligible. However, additional stresses can also occur within the dam if there is a sharp change in the shape of the foundation. This condition usually occurs at the abutments where foundation rock may change abruptly, but it can also occur along a long, wide river channel. Such conditions are eliminated wherever possible by excavating to a smooth profile.

The trial-load method is sometimes used in the analysis of arch dams.

FINITE ELEMENT METHODS

Dams of moderate height may be analyzed using the gravity and trial-load methods of analysis. However, in high dams, additional stresses that occur near the base of a dam, due to foundation yielding, may be important. Computer programs using finite element methods (FEM) permit the engineer to closely model the actual configuration of the structure and its interaction with the foundation. Either two- or three-dimensional finite element analyses may be used. The finite element method provides a more accurate picture of stress distribution and can more reliably predict the response of dams to earthquakes.

IV. STATIC STABILITY: ANALYTICAL METHODS

Two-Dimensional Finite Element Analysis

In most cases, two-dimensional (2-D) FEM may be used to model the cross section of a dam and predict the behavior of the dam with sufficient accuracy. The following attributes make the 2-D FEM useful in many situations:

- It is capable of analyzing the majority of problems associated with variations in the geometry of sections of the dam. Three-dimensional effects can be approximated by doing a 2-D analysis in more than one plane. (However, this is not true for an arch dam. A full 3-D analysis must be performed on an arch dam.)

- It is capable of solving for stresses economically even when great detail is necessary to attain sufficient accuracy.

- It is adaptable to gravity dam analysis when the assumption of planarity is used (that is, the assumption that a two-dimensional section is representative of all sections). The stress results for loading of typical transverse sections are directly applicable. Sections including auxiliary works can be analyzed to determine their stress distributions.

- It allows the foundation, with its possible wide variation in material properties, to be included with the dam in the analysis. Weak seams of material can be included in the foundation.

Three-Dimensional Finite Element Analysis

A three-dimensional (3-D) FEM is required under certain conditions, such as when:

- The structure or loading is such that conditions cannot be modeled suitably in two dimensions.

- The geometry of the problem is such that the stability of the dam depends upon the stress distribution parallel to its axis, as in a curved-in-plan structure.

- The cross section of the dam or its loading is not uniform along its longitudinal axis.

For simplicity, it may be preferable to approximate 3-D states of stress by combining the results of 2-D FEM studies done on transverse and longitudinal sections of the structure.

Analysis Of Results Of Finite Element Method Studies

When an FEM analysis is conducted for static loads, the basic stability criteria apply. Conventional factors of safety for sliding and overturning can be determined by integrating the stress distributions at the structure/foundation interface to calculate resultant locations and to determine if shear forces exceed dam or foundation capacities.

Because of the complexity of problems handled by FEM, computerized analysis is necessary. Review of FEM studies should concentrate upon the modeling assumptions made and the actual computer input to ensure that the computer model accurately represents the structural configuration of the dam and its foundation and that the material properties selected are representative of actual conditions.

It is essential that an experienced structural engineer review any FEM study. Subtle changes in material properties, boundary conditions, element type, and model geometry can have a significant effect on the results. The person interpreting the results must be able to recognize the influence of these factors on displacements and stresses in order to judge the reasonableness of the analysis. The results are difficult to verify by hand calculations.

LIMIT EQUILIBRIUM METHOD

The limit equilibrium method of analysis is based on principles of structural and geotechnical mechanics. These principles apply a factor of safety to the material strength parameters, assuming that the foundation materials are at a limit state or on the verge of shear failure. The analysis is performed in a manner that places the forces acting on the structure and foundation in sliding equilibrium.

A sliding failure will occur along a presumed failure surface when the applied shearing force exceeds the resisting material strength. A typical failure surface is illustrated in Figure IV-1. The failure surface can be any combination of plane and curved surfaces, but for simplicity all failure surfaces are assumed to be planes that form the bases of wedges. The critical failure surface with the lowest factor of safety is determined by an iterative process.

This method does not consider moment equilibrium, and only force equilibrium is satisfied in the analysis. The advantages of the limit-equilibrium method are its simplicity of calculation and its long history of reliability in producing designs that are stable against sliding. The main disadvantage is that no information on displacements is provided. Other disadvantages are that:

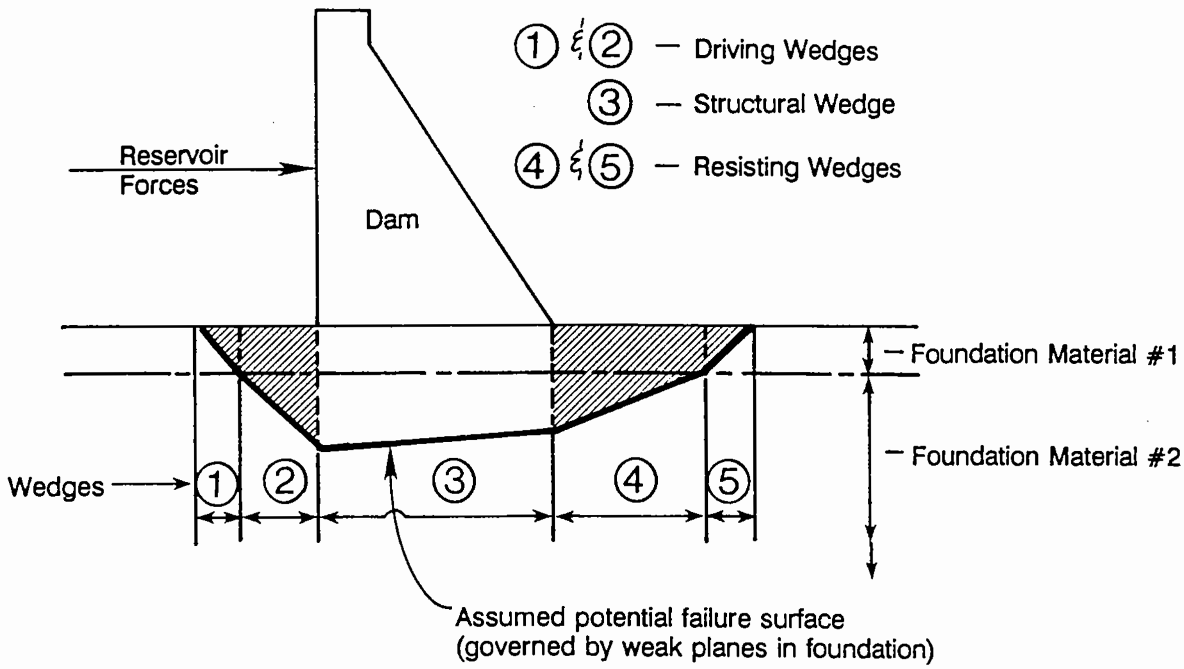
- Interaction between adjacent wedges is not considered.
- Strain compatibility is not considered.

A more complete description of this method can be found in the U.S. Army Corps of Engineers publication ETL 1110-2-256.

Continued . . .

LIMIT EQUILIBRIUM METHOD (Continued)

FIGURE IV-1. SLIDING STABILITY--LIMIT EQUILIBRIUM APPROACH



This method computes the sliding factor of safety required to bring the sliding mass, consisting of the structural wedge and the driving and resisting wedges, into a state of horizontal equilibrium along a given set of slip planes. The analysis requires a common factor for all wedges.

CRACKED BASE ANALYSIS

A dam must be safe either with or without uplift. Therefore, the concrete stresses and foundation reactions are computed with and without uplift to determine the critical load conditions (see Figure IV-2).

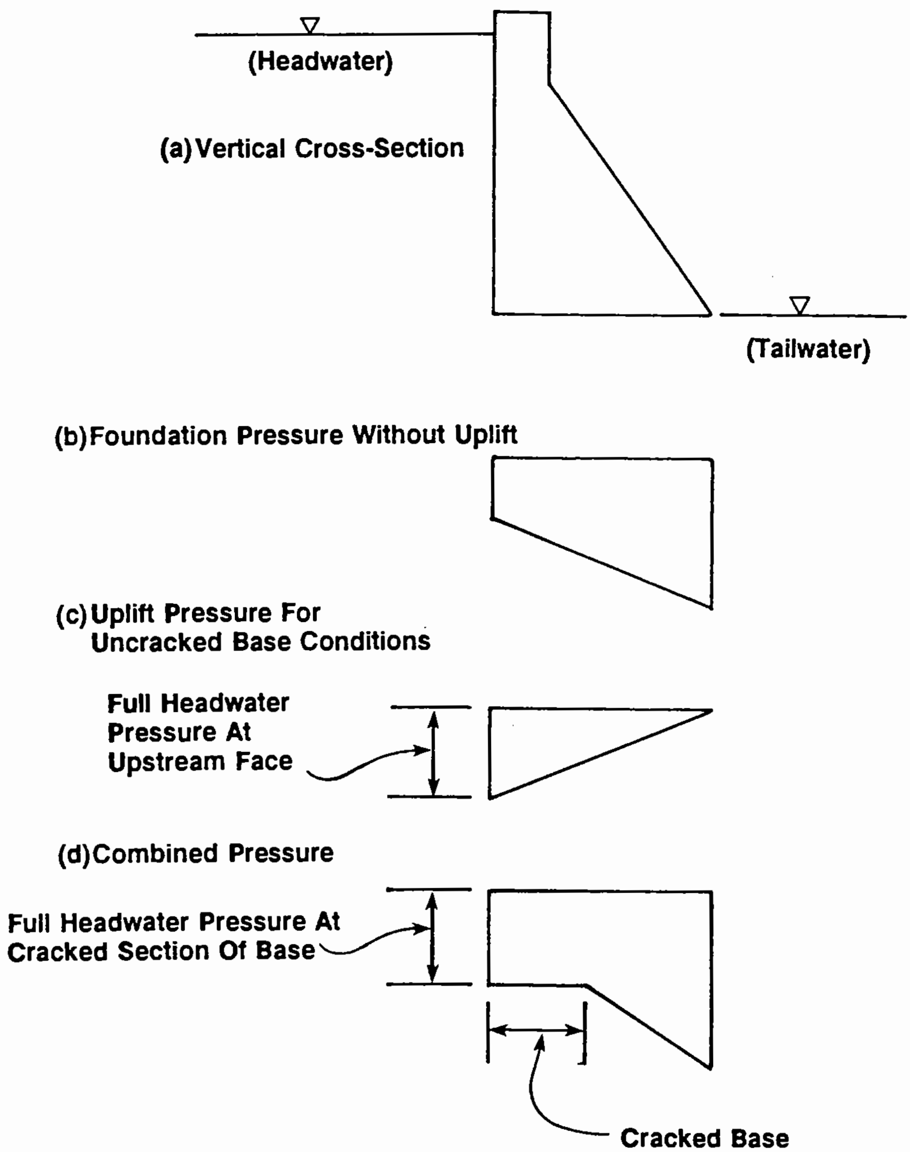
The Corps of Engineers and the Bureau of Reclamation have different approaches to determining base cracking. More complete descriptions can be found in the U.S. Army Corps of Engineers publications ETL 1110-2-256 and EM 1110-2-2200 and the Bureau of Reclamation publication Design Of Gravity Dams.

Continued . . .

CRACKED BASE ANALYSIS (Continued)

However, higher uplift pressures must be considered for the region of the base that is not in compression. This condition requires that the uplift diagram be modified and a cracked base analysis be performed.

FIGURE IV-2. BASE PRESSURES ACTING ON A GRAVITY DAM
(Per Design Of Gravity Dams)



Continued . . .

CRACKED BASE ANALYSIS (Continued)

The following are basic considerations of the cracked base analysis:

- The extent of base cracking is determined by establishing the allowable tensile stress (if any) that can be developed at the dam-foundation interface and then using static equilibrium procedures, which properly consider all force including uplift, to determine a base pressure distribution that satisfies both stress and equilibrium requirements. The base is considered cracked (no tensile strength) when tensile stress exceeds the allowable. For earthquake stability analyses, due to the oscillatory nature of earthquake loading, uplift is either assumed to be unaffected by seismic events or (if Bureau of Reclamation methods are used) assumed to be zero along the crack.

- Uplift may or may not be present. Therefore, base pressure distributions are determined with and without uplift to obtain maximum bearing pressures.

- Sliding factors are calculated using only friction on the cracked portion of the base, and friction plus cohesion on the uncracked portion.

- For the post-earthquake condition, normal and unusual load cases are reevaluated with proper consideration of the uncracked portion of the base.

Criteria

When analyzing new (unconstructed) dams, base cracking is usually not assumed for normal or unusual loading but may be assumed for extreme loading. However, at existing dams, base cracking is assumed for all loading conditions, provided that any potential crack that might propagate under load will stabilize analytically within the base of the dam and provided that adequate sliding safety factors are obtained using only the uncracked portion of the base.

When the extreme loading combination consists of an earthquake loading using the seismic coefficient method, the basic requirements for stability under normal and unusual combinations apply. The exception is that a cracked base analysis is allowed if the structure stabilizes when the analysis is conducted. An analysis should be conducted of the post-earthquake condition using the cracked base and modified material parameters to ensure stability under normal and unusual loading combinations.

USE OF COMPUTER PROGRAMS

Computer software is available to do many of the analyses described in this section. However, before using any particular software package, the user should have a thorough understanding of the assumptions made and the analytical procedures used. If a computer study is done, the study should document the name of the computer software used and sample input and output data.

Continued . . .

USE OF COMPUTER PROGRAMS (Continued)

Commonly used programs such as SAP4, STRUDL, ADAP, ADINA, EAGD, ADSAS, ABAQUS, and ANSYS are often accepted by design agencies without supporting documentation. Program documentation should be provided for any software that has not been thoroughly tested and proven to be accurate. Documentation should include samples of verification runs and a description of the analysis procedures used.

Input data should be checked for accuracy to ensure that the computer model will represent actual site conditions and parameters and realistically predict the structural behavior of the model and the loads to which it will be subjected.

Output data should be checked and compared to hand-calculated solutions to ensure that the basic laws of statics have been satisfied--that the summation of forces equals zero and the summation of moments equals zero.

IV. STATIC STABILITY: SUMMARY

SUMMARY: STATIC STABILITY

The methods described in Unit IV for analyzing the static stability of a concrete dam are summarized in Table IV-2.

TABLE IV-2. METHODS FOR ANALYZING STATIC STABILITY

Method	Description/Application
Gravity Method	Provides an approximate means for determining stresses in a cross section of a gravity dam. Is applicable to gravity sections with a vertical upstream face and a constant downstream slope and to those with variable slope on either or both faces.
Trial-Load Method	Used for gravity dams of moderate height that are made of a series of vertically cantilevered elements whose interaction will cause a twisting of the elements and torsional moments. Sometimes used in the analysis of arch dams.
Two-Dimensional Finite Element Method	Used to model the actual configuration of a structure and its interaction with the foundation. Can be used to analyze most problems associated with variations in the geometry of sections of the dam. Is capable of solving for stresses economically. Is adaptable to gravity dam analysis when the assumption of planarity is used. Allows the foundation to be included with the dam in the analysis.
Three-Dimensional Finite Element Method	Used where the structure or loading is such that conditions cannot be modeled suitably in two dimensions, where the stability of the dam depends on the stress distribution parallel to the dam's axis (as in a curved-in-plan structure), or where the cross section of the dam or its loading is not uniform.
Limit Equilibrium Method	Is based on principles of structural and geotechnical mechanics, applying a factor of safety to the material strength parameters and assuming that the foundation materials are at a limit state. Places the forces acting on the structure and foundation in sliding equilibrium. Considers only force equilibrium, not moment equilibrium.

Continued . . .

SUMMARY: STATIC STABILITY (Continued)

TABLE IV-2. METHODS FOR ANALYZING STATIC STABILITY (Continued)

Method	Description/Application
Cracked Base Analysis	Used to determine base cracking in a dam. In existing dams, base cracking is assumed for all loading conditions, provided the crack stabilizes within the base of the dam and adequate sliding safety factors are obtained using only the uncracked portion of the base.

UNIT V

SEISMIC STABILITY

V. SEISMIC STABILITY: OVERVIEW

INTRODUCTION

Seismic safety evaluations are performed to determine whether a dam would be able to withstand the stresses experienced during the design earthquake. This unit discusses six methods used to determine the expected response of dams to earthquakes. For each seismic stability analysis method, the text describes what the analysis can determine and the conditions that would warrant the use of a particular method of analysis.

V. SEISMIC STABILITY: ANALYTICAL METHODS

INTRODUCTION

Usually dams do not experience forces equal to those used for design. However, older dams will likely experience loads in excess of their design loads during a major earthquake, and damage can occur. Therefore a proper seismic safety evaluation is important to ensure that any damage will not result in a failure that involves a loss of life or property. Not only is the intensity of the ground motion important, but the displacements that may occur along faults or weak seams in the foundation can also lead to failure. During earthquakes, dams are subjected to dynamic forces that depend on the ground motion excitation, the properties (mass, stiffness, and damping) of the dam itself, and the mass of the impounded water.

The following methods are used for determining the response of dams to earthquakes:

- Overturning And Sliding Stability--Seismic Coefficient Method
- Internal Stress Analysis
- Response Spectrum Methods Of Analysis
  - Simplified Response Spectrum Method
  - Finite Element Response Spectrum Method
- Finite Element Acceleration-Time History Method
- Liquefaction And Collapse Analysis

A dynamic finite element analysis should be performed on existing dams in high seismic zones to accurately predict the dynamic stresses to which they may be subjected. Zones of high stress are evaluated to assess the extent of possible cracking. The postearthquake consequences of cracking should be evaluated by conducting sliding and overturning analyses for the normal reservoir level that consider the cracked section and material properties of the structure. Lower factors of safety derived from this analysis may be acceptable as long as catastrophic failure is not indicated.

V. SEISMIC STABILITY: ANALYTICAL METHODS

STABILITY CRITERIA

A seismic evaluation consists of the traditional overturning and sliding stability analysis, and a structural analysis to determine stresses within the dam. The evaluation approach is to determine (1) if the dam would fail during an earthquake of the greatest magnitude possible, and (2) if significant damage would occur during an earthquake of the greatest magnitude expected during a period equivalent to the economic life of the dam. These two events, termed the Maximum Credible Earthquake (MCE) and the Operating Basis Earthquake (OBE), are defined as follows:

- **Maximum Credible Earthquake (MCE):** The earthquake(s), combined with specific seismotectonic structures, source areas, or provinces, that would cause the most severe vibratory ground motion or foundation dislocation capable of being produced at the site under the currently known tectonic framework. MCE is determined by judgment based on all known regional and local geological and seismological data.

- **Operating Basis Earthquake (OBE):** The earthquake(s) that the structure is designed to be able to resist and still remain operational. OBE may be determined on a probabilistic basis with consideration given to the regional and local geology and seismology. It reflects the level of earthquake protection desired for operational or economic reasons. The OBE is often taken as the earthquake that has a 10 percent chance of being exceeded during a 100-year period.

When earthquake loading is calculated using dynamic or pseudodynamic methods, the following basic criteria apply:

- The dam must be capable of surviving an MCE without a catastrophic release of the reservoir. Inelastic behavior with associated damage is permissible under the MCE for the site.

- The dam must be capable of resisting an OBE safely (minor damage only) within the elastic range of the materials.

Tensile Stresses

Since tensile cracking is acceptable for the MCE loading, the significance of the tensile stresses that exceed the tensile strength of the concrete is evaluated to determine the extent of cracking and whether such cracking can lead to dam failure.

V. SEISMIC STABILITY: ANALYTICAL METHODS

Sliding Stability

To evaluate the significance of cracking, a sliding stability analysis is performed for the portion of the dam above the plane where the greatest cracking is expected. In addition, various nonlinear techniques are available to evaluate cracking in the dam, and the effect that cracking has on stability. Nonlinear analyses, however, are sensitive to the characteristics assumed for nonlinear slip or crack elements. Therefore, nonlinear analyses should only be performed by experts who have calibrated analyses with model testing or by other methods that ensure that the nonlinear model truly approximates actual behavior. SAP 80, ANSYS, ADINA, and ABAQUS are general purpose finite element computer software packages that include nonlinear slip elements and other nonlinear capabilities.

Overturning Stability

This type of gravity dam failure due to earthquake-induced excitation is not likely because of the wide base of the dam in relation to its height and because of the oscillatory nature of the motion and its short duration. The overturning stability of a gravity dam during an earthquake is considered to be adequate if the overturning criteria for the static load conditions are met, provided that the analysis includes equivalent static forces determined by the seismic coefficient method to represent the earthquake effects.

Stability After The MCE

After an earthquake the dam should be capable of containing the reservoir long enough to allow for any strengthening of the dam that is needed. For the normal static loading condition, the overturning and sliding stability should be checked assuming appropriate uplift in any cracked portion of the base as determined by the dynamic analysis. Often post-seismic stability is considered to be adequate if the resultant of all loads fall sufficiently within the base so as not to exceed 50 percent of the unconfined compressive strength of the concrete, and provided that the sliding factor of safety is 1.3 or greater.

Analysis For OBE

If the MCE loading analysis indicates that no cracking will occur, a stress analysis for the OBE is not required. However, effects of the OBE on the continued operation of essential equipment should be determined. If the level of the OBE is high enough to require a dynamic analysis, the simplest linear elastic analysis appropriate for the monolith is performed for the OBE loading using a 5 percent damping ratio. The combined maximum static and dynamic tensile stress should usually not exceed 15 percent of the static unconfined compressive strength of the concrete to assume no cracking occurs. This assumes that the lift joints are sound.

V. SEISMIC STABILITY: ANALYTICAL METHODS

OVERTURNING AND SLIDING STABILITY—SEISMIC COEFFICIENT METHOD

The seismic coefficient method is the simplest of all the seismic evaluation methods to use. In this method, a lateral force representing the inertial effects of the dam mass is applied at the center of gravity of the dam. The magnitude of this force is related to the seismic risk, as determined from seismic zone maps. A typical seismic zone map is shown in Figure V-1.

Table V-1 shows the seismic coefficients, expressed as a fraction of gravity, that are used by the U.S. Army Corps of Engineers.

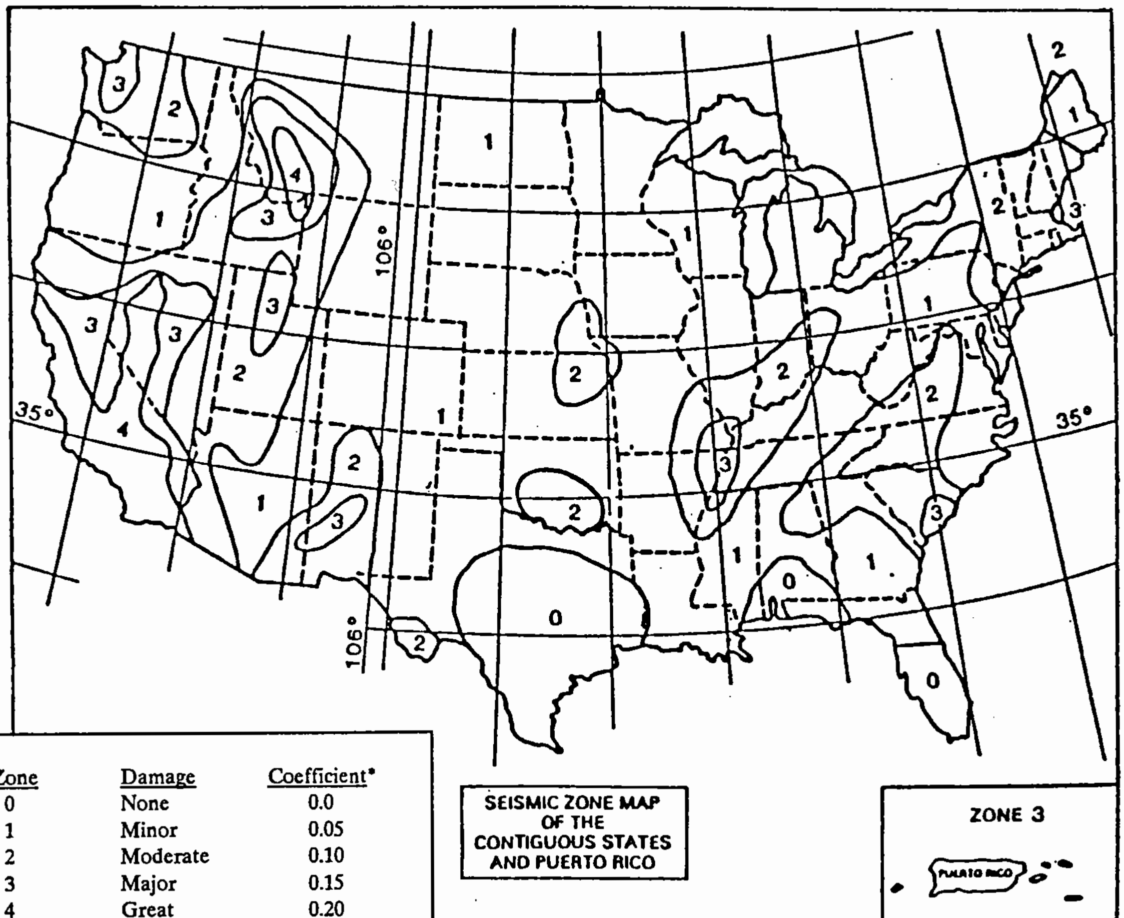
TABLE V-1. SEISMIC COEFFICIENTS

Zone	Damage	Coefficient
0	None	0.00
1	Minor	0.05
2	Moderate	0.10
3	Major	0.15
4	Great	0.20

Continued . . .

OVERTURNING AND SLIDING STABILITY--SEISMIC COEFFICIENT METHOD (Continued)

FIGURE V-1. SEISMIC ZONE MAP



Zone	Damage	Coefficient*
0	None	0.0
1	Minor	0.05
2	Moderate	0.10
3	Major	0.15
4	Great	0.20

* Coefficients are those used by the U.S. Army Corps of Engineers.

A disadvantage of the seismic coefficient approach is that it does not consider the response of the dam to the ground motion (that is, the dam is assumed to be rigid and to move in unison with the ground). Therefore, this method can underestimate the lateral force that will occur on the dam during a major earthquake.

Continued . . .

V. SEISMIC STABILITY: ANALYTICAL METHODS

OVERTURNING AND SLIDING STABILITY—SEISMIC COEFFICIENT METHOD (Continued)

However, the seismic coefficient method was traditionally used for the design of older dams and is currently used for overturning and sliding stability analyses. This is because dams and structures in general do not become unstable during earthquakes because the ground motion is brief, and any rocking or sliding of the dam on its foundation will dissipate energy and somewhat sever the link between the exciter (the ground) and the responder (the dam). Therefore, the forces represented by prescribed seismic coefficients are usually considered to be adequate for seismic stability analyses.

The seismic stability analysis must also consider the hydrodynamic effects of the reservoir. Methods for doing this are similar to those for internal stress analysis.

INTERNAL STRESS ANALYSIS

In addition to the stability analysis, a dynamic stress analysis is normally performed for a gravity dam when one of the following conditions exists:

- The dam is 100 or more feet high and the peak ground acceleration (PGA) at the site is greater than 0.2g for the MCE.
- The dam is less than 100 feet high and the PGA at the site is greater than 0.4g for the MCE.
- The dam is in a weakened condition to the extent that it does not meet the stability criteria for the static loading or earthquake loading.

The dynamic methods of stress analysis determine the structural response based on the dynamic characteristics of both the structure and the nature of the earthquake loading. Dynamic methods are used largely to evaluate the potential for excessive stressing and cracking of the concrete dam itself, particularly in the upper portions of gravity and arch dams, and at any location in buttress dams where there are abrupt changes in the cross section.

Procedures

A dynamic analysis investigation includes the following steps:

1. Review the geology, seismology, and contemporary tectonic setting, and determine earthquake sources.
2. Select the following:
   - Candidate MCE and OBE magnitudes and locations.
   - Attenuation relationships for the candidate earthquakes.

Continued . . .

Procedures (Continued)

3. Select controlling MCE and OBE from the candidates on the basis of the most severe ground motions at the site, and determine evaluation response spectra for the controlling earthquakes.

4. If nonlinear behavior (cracking) is anticipated, an acceleration-time history analysis is usually warranted. When acceleration-time history analyses are needed, select appropriate acceleration-time records compatible with the evaluation response spectra.

5. Select dynamic materials properties for the concrete and foundation.

6. Select dynamic methods of analysis to be used.

   Current methods generally use the **modal analysis technique.** This technique is based on the fact that, for certain forms of damping that are reasonable models for many structures, the response in each natural mode of vibration can be computed independently of the others, and the modal responses can be combined to determine the total response.

   Modal dynamic methods of analysis that can be used for gravity dams include:

   - Simplified response spectrum method
   - Finite element methods:
     - Response spectrum method
     - Acceleration-time history method

   When a dynamic stress analysis is required, the analysis should begin with the simplest methods of analysis and progress to more refined methods if needed.

7. Perform the dynamic analysis.

8. Evaluate stresses determined from the dynamic analysis to see if they are excessive.

RESPONSE SPECTRUM METHODS OF ANALYSIS

In the response spectrum method, the maximum response in each mode, in the form of equivalent loads, is computed directly from the earthquake response spectrum and the structure's dynamic characteristics. The responses are combined to obtain a total maximum response. Then the internal stresses in the concrete are computed by a static analysis of the structure subjected to the equivalent lateral loads and added to the static load stresses.

Continued . . .

V. SEISMIC STABILITY: ANALYTICAL METHODS

RESPONSE SPECTRUM METHODS OF ANALYSIS (Continued)

The following seismic loading parameters are required for this method of analysis:

- Earthquake response spectrum for the site
- Structure dynamic properties of the concrete (unit weight, Young's modulus of elasticity, damping, and Poisson's ratio)

When the foundation is to be included in the analyses, the following parameters for the foundation are also needed:

- Moduli of elasticity
- Poisson's ratio

Two response spectrum methods are used: the simplified method and the finite element method.

Simplified Response Spectrum Method Of Analysis

This method of analysis computes the maximum earthquake loading for a typical nonoverflow section of a gravity dam in its fundamental mode of vibration in response to the horizontal component of the ground motion.

The dam is treated as if it is fixed to a rigid foundation, and hydrodynamic effects are modeled as an added mass of water moving with the dam. The amount of the added mass depends on the fundamental frequency of vibration.

Finite Element Response Spectrum Method Of Analysis

A more rigorous dynamic analysis of a gravity dam can be obtained by using one of the available finite element software packages, such as SAP, GTSTRUDL, and ANSYS, which can model static and dynamic responses of linear two- and three-dimensional structural systems. The hydrodynamic effects are modeled as an added mass of water moving with the dam. The foundation can be modeled as a finite element grid or half space. These programs have the capability to include the response of the higher modes of vibrations, the interaction effects of the foundation and any surrounding soil, and both the horizontal and vertical components of the ground motion.

The finite element program computes the natural frequencies of vibration and corresponding mode shapes for the modes of interest. Earthquake loading is computed from earthquake response spectra for the response of the dam in each mode of vibration to the horizontal and vertical components of ground motion. These modal responses are combined to obtain the maximum total response. Stresses are computed by a static analysis of the dam, treating the earthquake loading as an equivalent static load.

V. SEISMIC STABILITY: ANALYTICAL METHODS

FINITE ELEMENT ACCELERATION-TIME HISTORY METHOD

The acceleration-time history method computes the natural frequencies of vibration and corresponding mode shapes for each mode of interest. The response of each mode, in the form of equivalent lateral loads, is calculated for the entire duration of the earthquake acceleration-time record, starting with initial conditions, taking a small time interval, and computing the response at the end of each time interval. The modal responses are added together for each time interval to yield the total acceleration-time response. The stresses are then computed by a static analysis for each time interval.

This method requires either a general purpose finite element computer program or one of the following special purpose software packages:

- **EADHI (Earthquake Analysis Of Gravity Dams Including Hydrodynamic Interaction).** This program can model static and dynamic responses of linear two-dimensional systems. The hydrodynamic effects are modeled using the wave equation. The compressibility of water and structural deformation effects are included in the computation of hydrodynamic pressures. EADHI was developed assuming a fixed base for the dam.

- **EAGD84 (Earthquake Analysis Of Gravity Dams Including Hydrodynamic And Foundation Interaction).** This program can model static and dynamic responses of linear two-dimensional systems, including both hydrodynamic and foundation interaction. It is the most rigorous two-dimensional earthquake analysis program available to date for gravity dams.

The use of acceleration-time history methods is appropriate whenever it is necessary to vary stresses with respect to time in order to evaluate the extent and duration of an overstressed condition. The EADHI and EAGD84 programs can also be used to check the accuracy of Westergaard's lumped mass approach, which is used by the general purpose finite element programs for modeling hydrodynamic interaction effects.

Seismic Loading Parameters

The following seismic loading parameters are needed in the acceleration-time history method of analysis:

- Earthquake acceleration-time record or synthetic accelerogram
- Compressive and tensile strengths of the concrete

When the foundation is to be included in the analysis, the following parameters for the foundation are also needed:

- Moduli of elasticity
- Poisson's ratio
- Unit weights for each material
- Damping characteristics for each material
- Geometric descriptions of the materials (thicknesses, lateral extent)

Modeling Of Hydrodynamic Effects

EADHI models hydrodynamic effects directly using the wave equation and takes into account the compressibility of water and the deformation of the structure. In other finite element programs and for the seismic coefficient method, this effect can be approximated by determining and attaching "added masses" to the upstream face of the dam. The increased mass results in an increased inertial resistance to motion of the structure and increases the period of vibration of the structure. Both affect the peak acceleration, velocity, displacement, and force the structure experiences during an earthquake.

Evaluating Linear Dynamic Analysis Results

Linear dynamic analysis results are evaluated in terms of compressive and tensile strengths of the concrete. The compressive stresses resulting from the combination of static and earthquake loads should be substantially less than the dynamic strength capacity of the concrete. Meeting this requirement has not been a problem.

However, since tensile cracking is acceptable for the MCE loading, the significance of tensile stresses that exceed the tensile strength of the concrete is not as easily evaluated. To evaluate such excess stresses, sound engineering judgment based upon the expected effects of nonlinear behavior and the past performance of dams under similar earthquake loadings is required. The magnitude of overstress, the location of overstress, and the duration of the earthquake are important factors in the evaluation.

To estimate the extent of cracking, nonlinear behavior resulting in stiffness degradation and energy absorption is considered. Nonlinear behavior reduces the peak values of tensile stress and the extent of tensile zones. Thus, large tensile stresses from a linear elastic analysis do not necessarily indicate an unsafe condition. In fact, it has been postulated that "apparent tensile strength" values (values exceeding those established by testing) should be used when evaluating linear finite element results.

LIQUEFACTION AND COLLAPSE ANALYSIS

Most concrete dams are founded on rock and thus are not subject to liquefaction or collapse distress. However, dams founded on cohesionless soils should be evaluated.

The response of foundation soil to saturation and cyclic shear stresses relates in part to the in situ condition of the soil--whether contractive or dilatant.

Contractive Soils

If a loose to medium dense, saturated, cohesionless material is subjected to cyclic shear stresses of a sufficient magnitude, the volume of the soil mass will tend to decrease. This condition is termed contractive. If drainage is restricted or the permeability is sufficiently low, the reduction in volume results in an increase in pore water pressure. As the pore pressure ratio approaches 100 percent, the material will lose some, most, or all of its shear strength. Sudden collapse, volume changes, severe deformation, or sliding may result.

V. SEISMIC STABILITY: ANALYTICAL METHODS

Dilatant Soils

Dense to very dense soil deposits tend to increase in volume during shear or cyclic loading. This condition is termed dilatant. Dilatant soils generally are not susceptible to liquefaction because the excess pore pressure, if saturated, is temporarily in tension. This tension temporarily increases the undrained shear strength to values somewhat greater than the normal drained shear strength without dilation.

Liquefaction Potential

The following factors influence the liquefaction potential of soil:

- Soil type
- In situ density or void ratio
- Initial confining pressure
- Intensity and duration of ground shaking
- Method of soil placement (soil structure)
- Period under sustained load
- Previous strain history
- Lateral earth pressure coefficient and degree of overconsolidation
- Degree of saturation
- Permeability rate in relation to excess pore pressure buildup during cyclic loading

For a given earthquake magnitude, duration, and base acceleration, the liquefaction potential of soil:

- Increases with . . .
  - Increasing confining stress
  - Decreasing in situ density
  - Decreasing permeability

- Decreases with . . .
  - Elapsed time since prior seismic loading
  - Increasing overconsolidation
  - Increasing initial in situ shear stress

Fine-grained, cohesive materials with a medium-stiff to stiff relative consistency have a very low potential for liquefaction or collapse. Thus dams constructed on clay soil foundations may endure strong shaking with no apparent damage.

It is generally accepted that cohesionless sand-sized material has a high potential for liquefaction or collapse. When deposited in a loose to medium-dense state, such material has very low permeability and approaches undrained loading with large excess pore pressures during cyclic shaking. Cyclic shear strains frequently result in contraction, excess pore water pressures, and very low, liquidlike shear strength.

V. SEISMIC STABILITY: ANALYTICAL METHODS

Methods Of Analysis

Two basic approaches are used to evaluate the cyclic liquefaction and collapse potential of a deposit of suspect soils that are subjected to earthquake shaking:

- **Empirical methods** based on field observations of the performance of similar deposits in previous earthquakes, correlations between sites that have and have not liquefied or collapsed, and Relative Density or Standard Penetration Test (SPT) blowcount data.

- **Analytical methods** based on the laboratory determination of the consolidation collapse potential, cyclic liquefaction strength characteristics, excess pore pressure ratios, and the use of dynamic site response analysis to determine the magnitude of earthquake-induced shearing stresses.

Enough worldwide data have appeared in the literature that the empirical methods have been generally accepted as the state-of-the-art approach to liquefaction and collapse analysis.

Both empirical and analytical methods require the level of ground acceleration at a site to be defined as a prerequisite for assessing liquefaction potential. This level is often established from relationships between earthquake magnitude, distance from the epicenter, and peak acceleration.

For conventional evaluations using a "total stress" approach, the two methods are similar, differing only in the manner in which the field liquefaction strength is determined. In the "total stress" approach, undrained liquefaction strengths are normally expressed as the ratio of an equivalent uniform or average cyclic shearing stress acting on horizontal surfaces of the soil to the initial vertical effective stress.

Once a liquefaction strength curve has been established, liquefaction potential is evaluated from comparisons with estimated earthquake-induced shear stresses.

In evaluating the collapse potential alone, undisturbed samples are loaded according to the loads imposed by the dam and then saturated. The amount of collapse is evaluated and quantified. In this analysis, dynamic loads or analyses are not used. The collapse occurs from structural breakdown of the soil itself.

V. SEISMIC STABILITY: SUMMARY

SUMMARY: SEISMIC STABILITY

The methods for analyzing the seismic stability of an embankment dam are summarized in Table V-2.

TABLE V-2. METHODS FOR ANALYZING SEISMIC STABILITY

Method	Application
Overturning And Sliding Stability--Seismic Coefficient Method	Used for overturning and sliding stability analyses. A lateral force representing the inertial effects of the dam mass is applied at the center of gravity of the dam. The magnitude of this force is related to the seismic risk according to seismic zone maps. Does not consider the response of the dam to ground motion.
Internal Stress Analysis	Used to evaluate the potential for excessive stressing and cracking of a concrete dam particularly in the upper portions of gravity and arch dams, and at any location in buttress dams where there are abrupt changes in the cross section.
Simplified Response Spectrum Method	Computes the maximum earthquake loading for the linear response of a typical nonoverflow section of a gravity dam in its fundamental mode of vibration to the horizontal component of the ground motion.
Finite Element Response Spectrum Method	Uses computer software to model static and dynamic responses of linear two-and three-dimensional structural systems.
Finite Element Acceleration-Time History Method	Computes the natural frequencies of vibration and corresponding mode shapes for each mode of interest. Is appropriate whenever it is necessary to vary stresses with respect to time in order to evaluate the extent and duration of an overstressed condition.
Liquefaction And Collapse Analysis	Uses empirical or analytical methods to evaluate the cyclic liquefaction and collapse potential of dams founded on cohesionless soils.

UNIT VI

REMEDIAL ACTION

VI. REMEDIAL ACTION: OVERVIEW

INTRODUCTION

During the course of investigation and analysis, deficiencies may be identified that require some type of remedial action. Remedial measures may be of an emergency and temporary nature, or they may be long-term treatments:

- **Emergency and temporary measures:** Measures that must be undertaken immediately to prevent failure of the dam or alleviate conditions that could lead to failure of the dam.

- **Long-term measures:** Repairs or improvements of a permanent nature that are used to correct the identified deficiencies.

This unit provides brief descriptions of the short- and long-term measures that may be used when deficiencies are identified that threaten the static or seismic stability of a concrete dam.

In addition to these brief descriptions, it may be helpful to review the defensive design measures discussed in Unit II, which in many cases are quite similar to the remedial treatments presented here.

VI. REMEDIAL ACTION: EMERGENCY AND TEMPORARY MEASURES

INTRODUCTION

On occasion, deficiencies discovered during operation or inspection of a concrete dam may require immediate action to:

- Prevent failure of the dam.
- Alleviate conditions that could lead to failure of the dam.
- Alleviate conditions that could impair the dam's ability to operate as intended for flood protection.

Emergency and temporary measures are normally used until long-term treatments can be put in place. In identifying remedial measures, it is important that they be selected carefully to ensure that the short-term solution does not cause a long-term problem or conflict with the installation of long-term solutions.

CONDITIONS REQUIRING IMMEDIATE ACTION

The following conditions may require immediate action:

- Erosion of foundation materials
- Leakage through concrete or foundation and abutment materials that increases with time or shows evidence of removing material
- Instability of reservoir or abutment slopes or the foundation along the toe
- Excessive settlement

These conditions may call for immediate action because they can indicate or lead to events such as:

- Breach of the dam
- Overtopping of the dam due to seiche waves generated by upstream landslides
- Breaching of the foundation or weakening of the foundation to a point where a piping, sliding, or overturning failure occurs

MEASURES TO BE CONSIDERED

When it is determined that immediate corrective action is required, you should consider the following measures:

- Drawing the reservoir down
- Sealing or draining cracks
- Modifying operational procedures
- Buttressing unstable slopes
- Emergency planning (generally associated with reservoir drawdown)

VI. REMEDIAL ACTION: EMERGENCY AND TEMPORARY MEASURES

Drawing The Reservoir Down

When leakage or instability of the dam is the problem, it may be appropriate to draw the reservoir down. Immediate drawdown in this situation may have two major benefits:

- By reducing the hydrostatic pressures and reservoir load, drawdown may slow down or stop the processes that can lead to dam failure.

- By reducing the amount of impounded water, drawdown will reduce the impact downstream if a failure does occur.

Sealing Or Draining Cracks

When cracks in the dam or foundation are leading to significant leakage or erosion of materials, the cracks may be sealed to reduce the amount of leakage and to lessen the potential for erosion or piping. Crack sealing with proper crack drainage can reduce detrimental uplift pressures.

It is advisable to provide for drainage of the cracks, so that the leaking water is conducted to a suitable location in the drainage system. Drainage alone also can be used to relieve internal pressures that tend to keep the cracks open and propagate them.

Modifying Operational Procedures

For abutment and reservoir rim slope instability problems, it may be possible to modify operational procedures to prevent rapid fluctuations of the reservoir level. Such fluctuations can lead to sloughing and slope instability.

When discharges are causing erosion of concrete and foundation materials at the toe of the dam, operational procedures should be modified to reduce discharges or to direct them away from the affected area.

Buttressing Unstable Slopes

Unstable reservoir slopes or excavations may require buttressing with large, free-draining material. Buttressing can be used to improve stability, control piping, and allow internal hydrostatic pressures to dissipate safely.

Emergency Planning

The details of emergency planning are covered in the TADS modules Evaluation of Facility Emergency Preparedness and How To Develop And Implement An Emergency Action Plan. Each dam should have an emergency action plan, and dam owners and operating personnel should be familiar with the plan and their responsibilities.

VI. REMEDIAL ACTION: LONG-TERM MEASURES

INTRODUCTION

Long-term measures are repairs or improvements of a permanent nature that are used to correct identified deficiencies. Significant time is often required for planning and construction of long-term treatments. Therefore, emergency and temporary measures may be used to provide short-term solutions until permanent treatments can be implemented.

Several types of long-term measures can be used to stabilize a structure and/or its foundation. In many cases, long-term solutions also include monitoring to evaluate continuing deterioration, and early warning systems to mitigate the effects of failure.

RESTORING STRUCTURAL INTEGRITY

Modifications or repairs can be made to the dam to restore structural integrity. These modifications include:

- Increasing freeboard
- Adding weight
- Anchoring
- Adding thrust blocks
- Repairing concrete

Increasing Freeboard

Freeboard should have been set at or above the minimum elevation required by regulatory requirements and/or agency criteria. To eliminate excessive overtopping, it may be necessary to increase the amount of freeboard on a concrete dam above the minimum elevation. Long-term measures for increasing freeboard may include:

- Raising the top of the dam.

- Adding parapet walls to the top of the dam.

- Adding floating log booms to reduce wave setup from earthquake shaking fault displacement in the reservoir, tilting of the reservoir, and landslides and to reduce potential for plugging of inlets by trees, debris, ice, and other material.

- Restricting recreational activity near the dam to reduce wave setup.

- Adding trash guards to prevent plugging of inlets.

- Adding outlet gates, conduits, or other means of lowering the reservoir during ice-forming weather or other extreme conditions.

- Increasing spillway capacity.

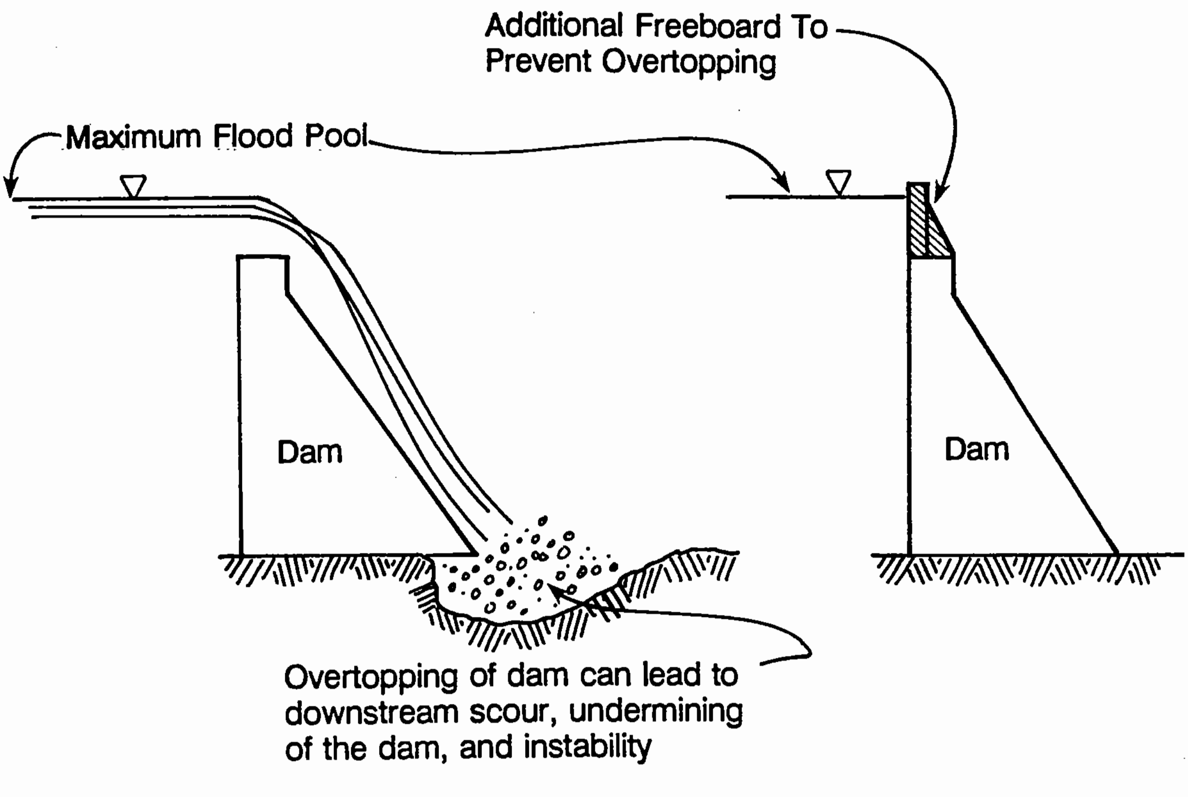
Continued . . .

VI. REMEDIAL ACTION: LONG-TERM MEASURES

Increasing Freeboard (Continued)

Adding freeboard as a remedial preventive measure is shown in Figure VI-1. In-depth technical analysis and collective consultation by engineering geologists, hydrologists, and hydraulic and structural engineers are required in developing alternatives and selecting the best alternative. Stability should be reanalyzed if maximum pools are raised.

FIGURE VI-1. ADDING FREEBOARD AS A REMEDIAL MEASURE



Adding Weight

Adding mass to a concrete structure will increase its sliding stability by increasing frictional resistance to driving forces. Weight may be added in two ways:

- By filling voids in the structure with concrete or other suitable materials.
- By adding concrete to the dam exterior. When concrete is added to the cross section, it must be anchored, bonded, and/or keyed to the existing structure to ensure monolithic action of the entire mass.

VI. REMEDIAL ACTION: LONG-TERM MEASURES

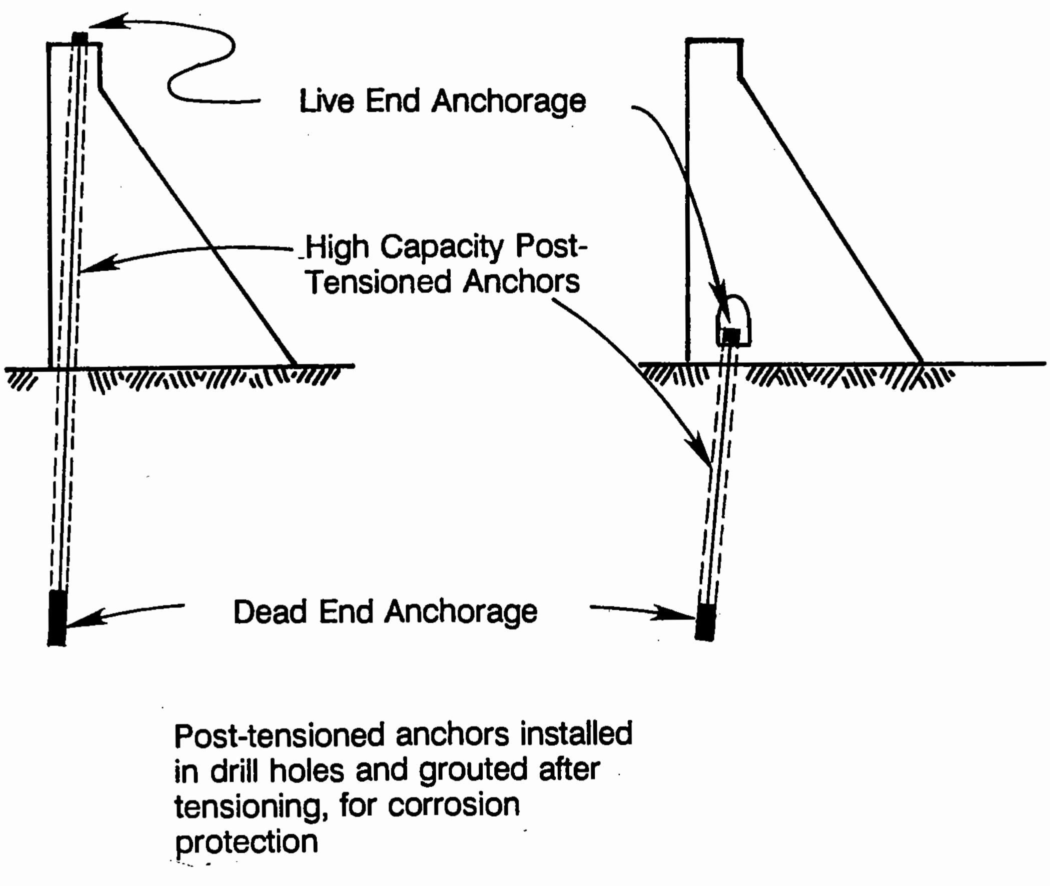
Anchoring

Anchoring or post-tensioning has been used as a remedial measure to increase stability in three main types of application:

- Post-tensioning of structural elements that have lost or may lose their internal strength
- Post-tensioning of structural elements or mass sections to restore or preserve external stability
- Post-tensioning of geologic formations to increase their stability or suitability for structural support (this application will be discussed under restoring foundation integrity)

A post-tensioned anchorage system for a gravity dam is shown in Figure VI-2.

FIGURE VI-2. ANCHORING TO IMPROVE STABILITY



Installation Of Anchoring

Post-tensioning is usually accomplished on existing structures by means of steel rods or cables inserted in holes drilled into nonyielding materials, such as massive bedrock or massive structures. The ends are normally anchored with epoxy or cement grout or with mechanical devices.

Where possible (at a wall or beam) the anchor ends may simply be anchored onto the back side of the structure using steel bearing plates with rod nuts or cable clamps. Post-tensioned beams typically have anchor plates on the ends for anchoring the rods or cables.

Installation details, such as depth and number of anchors and the length of embedment required to provide anchorage, depend on various factors:

- Type and condition of the rock or structure
- Amount of tension required
- Amount of stress redistribution required at the anchor ends

Applying Tension

Once anchored, a predetermined amount of tension (pull) is applied to the rod or cable. The tension is transferred to the anchorage system at the face of the structure, end of the beam, or other such location.

Post-tensioning systems generally must be tested by proof, performance, field pull testing, or all of these methods.

Specific Applications For Post-Tensioning

The following are specific applications for which post-tensioning has been used:

- To close tension cracks in damaged beams and other structures by transferring the existing tension from the concrete to the rods.

- To anchor slabs, aprons, or footings to bedrock or to other existing structures.

- To anchor a massive structure to its foundation to ensure that there are positive compressive forces within the structure in the vicinity of the foundation and at the structure/foundation interface.

- To anchor the base of a structure to its foundation so as to provide stability against overturning or a "second line of defense" where overturning stability is uncertain.

Continued . . .

Specific Applications For Post-Tensioning (Continued)

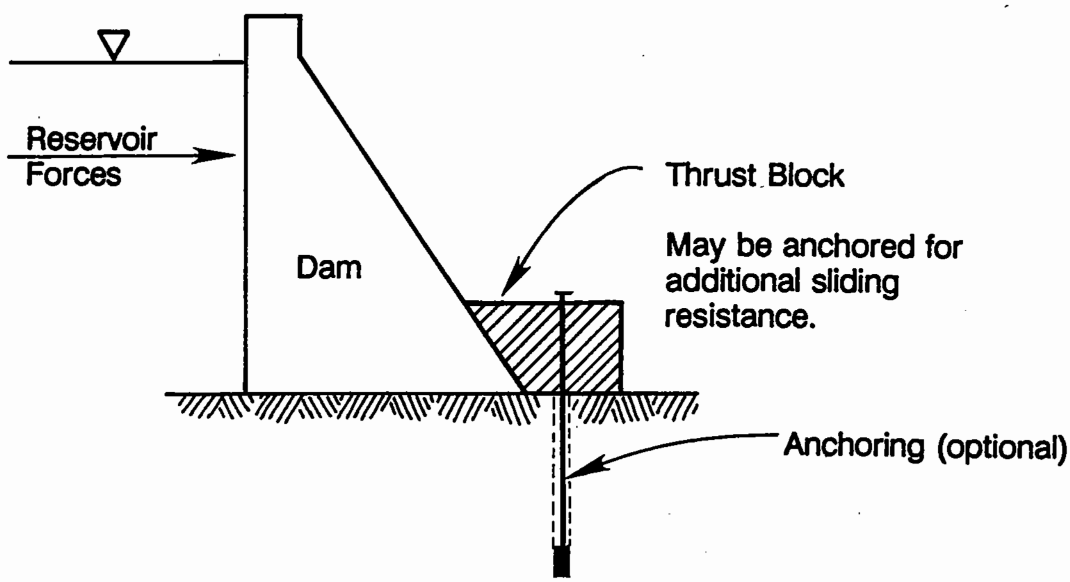
- To improve sliding resistance by applying compressive loads normal to the failure surface.
- To force closure of cracked structures that have been damaged by excessive tensile forces as a result of environmental conditions.

Agency policies, criteria, and procedural guidelines that apply to post-tensioning should be carefully reviewed. It is important to consult experienced engineering geologists and structural engineers during preliminary evaluation of alternatives and final technical evaluations.

Adding Thrust Blocks

Thrust blocks can be added to the downstream toe to increase passive resistance to sliding. Thrust blocks are either concrete blocks or anchored portions of the downstream foundation which must move in order for the structure to slide. A deformation analysis of the dam/foundation blocks should be performed to account for strain compatibility and to ensure adequate factors of safety against sliding. A typical thrust block arrangement is shown in Figure VI-3.

FIGURE VI-3. ADDING THRUST BLOCKS TO IMPROVE SLIDING RESISTANCE



VI. REMEDIAL ACTION: LONG-TERM MEASURES

Repairing Concrete

Concrete may be repaired by replacing deteriorated concrete or repairing cracks. While concrete repairs are rarely used as a remedial measure to stabilize a dam, they can be used to increase the overall integrity, seal the concrete against further deterioration, and improve cosmetic appearance.

Cracks that interfere with the interaction of various components of the structure can be grouted with an epoxy or cement grout. Grouting helps to reestablish the interaction and thereby restore structural integrity.

Epoxy- and polyester-based resins are used for repairing concrete because of their strength and exceptional adhesive properties. These materials are used both for surface treatment and to seal cracks. For example:

- Resins with low sensitivity to water have been used as bonding agents between old and new concrete.
- Epoxy-based and polyester-based resins have been widely used for facing on dams and other hydraulic structures.
- Resins have been used for injection into cracks. The viscosity of the resin can be varied from pumpable mortar to very thin grout.

RESTORING FOUNDATION INTEGRITY

The foundation can be modified to strengthen weak zones or discontinuities, to reduce seepage pressures acting on potential failure planes, to reduce uplift pressures, or to prevent erosion of foundation material from abutment and toe areas. Modifications may involve:

- Reducing seepage and uplift pressures
- Anchoring
- Adding abutment and toe protection to prevent scour

Reducing Seepage And Uplift Pressures

Seepage and uplift pressures may be reduced by improving drainage systems, grouting foundations and abutments, and adding cutoffs.

Improving Drainage Systems

Inadequate drainage is one of the most common sources of stability problems in dams. Although seepage nearly always occurs and may be relatively safe, excessive foundation/abutment seepage may lead to piping, erosion, sloughing, and development of destabilizing uplift pressures. Internal seepage can lead to leaching, staining of exterior surfaces, freeze-thaw damage, vegetative growth on concrete surfaces, and instability.

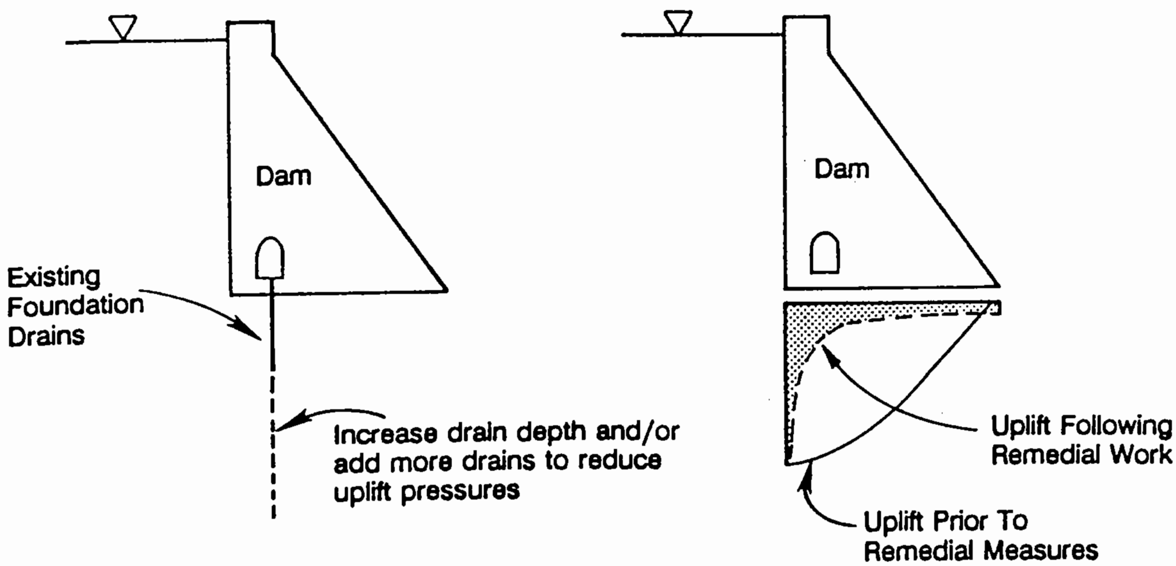
Continued . . .

VI. REMEDIAL ACTION: LONG-TERM MEASURES

Improving Drainage Systems (Continued)

Seepage and uplift pressures may be reduced by expanding or rehabilitating an existing drainage system. The addition of drains reduces the magnitude of uplift developed beneath a structure. This reduction in turn increases the effective weight acting on failure planes and the corresponding frictional resistance to driving forces. Figure VI-4 illustrates improvement of a drainage system to reduce uplift pressures.

FIGURE VI-4. PROVIDING ADDITIONAL DRAINS AND INCREASING DRAIN DEPTH



Some agencies specify that only drains that discharge to an open, accessible area that permits visual inspection and maintenance and that are monitored regularly by instrumentation can be relied upon for uplift relief. (In other words, a closed drainage system that cannot be monitored either visually or by instrumentation may be used, but it is not considered effective in relieving uplift pressures.) Other agencies require factors of safety of at least 1.0 in the event of drainage system malfunction.

Continued . . .

VI. REMEDIAL ACTION: LONG-TERM MEASURES

Improving Drainage Systems (Continued)

Several different drainage features may be used, depending on the severity of the situation:

- Added or extended foundation drains
- Blanket drains of clean, coarse gravels
- Filter blankets
- Relief wells
- Trench drains

The most appropriate solution usually depends on the location of the problem or the type of foundation material in which the problem occurs. Table VI-1 presents a summary of types of drainage problems that may occur, specific drainage features that are commonly used to deal with them, and appropriate uses or locations of each feature.

Control and measurement are important when improving a drainage system. Piezometers and volume measuring devices should be in place before drainage is installed. These devices make it possible to establish baseline piezometric profiles and flow quantities and to evaluate the effect of added drains. Continued monitoring throughout the life of the structure is necessary to identify any deterioration due to clogging or changes in reservoir conditions.

Continued . . .

Improving Drainage Systems (Continued)

TABLE VI-1. DRAINAGE PROBLEMS AND SOLUTIONS

Problems	Drainage Features	Where Used
Uplift pressures in foundation	Blanket drains of clean, coarse, highly permeable gravel	Foundations of reasonably homogeneous rock or soil
	Finer filter material beneath drain to prevent piping from foundation	Where soil is fine enough to move into gravel drain
	Relief wells, which may operate independently or in conjunction with blanket drain	Where foundation is stratified rock or soil or irregularly fractured rock of random nature
Seepage pressures that may cause sliding and sloughing of slopes	Trench drains of clean, coarse gravel; perforated drain pipes	Seepage area in downstream groin area
	Finer filter material placed beneath drain	Where soil is fine enough to move into gravel drain
	Trench drain or horizontally inserted drain pipes	Seepage traveling in a confined zone
	Area-type treatment of free drainage filter and drain blankets	Seepage through entire abutment
	Berms of drain and filter materials	Seepage low on abutment or reservoir slope
Seepage exit gradients that may cause piping and internal soil erosion (especially in downstream toe)	Blanket drains of clean, coarse gravels Relief wells Trench drains of clean gravel placed transversely along downstream toe and allowed to exit freely at ground surface Riprap at surface of trench drains to protect from scour	Sand or silt foundation soil (or soils in filled joints of fractured rock) of medium to low plasticity or nonplastic (check for piping potential).
	Filter materials to protect drain materials from infiltration by soil	Where soil is fine enough to move into gravel drain
Uncontrolled seepage within dam	Internal drainage into galleries, ports, tubes, etc.	Seepage within dam

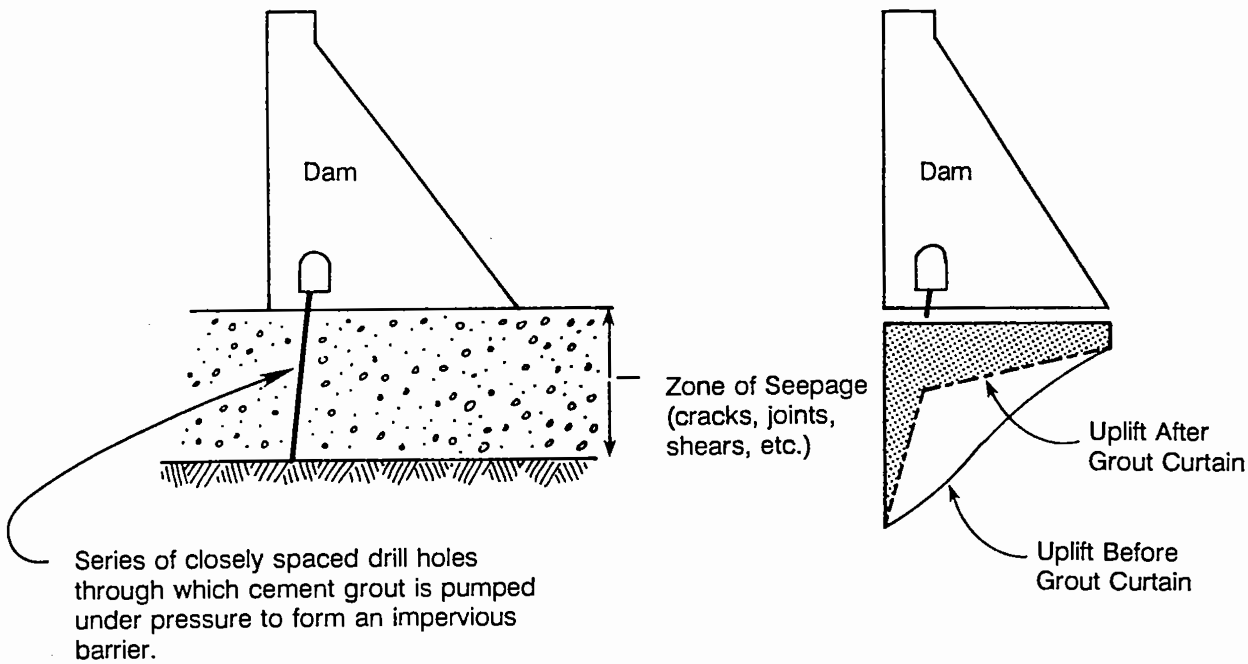
VI. REMEDIAL ACTION: LONG-TERM MEASURES

Grouting Foundations And Abutments

Where seepage flow through the foundation or abutments is a problem or seepage pressures are undesirably high, pressure grouting may be done to install a grout curtain or improve an existing one. A grout curtain is illustrated in Figure VI-5.

When installing grout curtains in existing dams, the reduction in **seepage quantity** can be visually observed and monitored and the grouting adjusted accordingly. However, the effectiveness of a grout curtain in reducing **uplift pressures** is not so easily monitored. It is common practice to install instrumentation on the downstream side of the grout curtain and within the drainage systems to monitor the effectiveness of the grouting.

FIGURE VI-5. GROUT CURTAIN CUTOFF



NOTE: Grouting will reduce the volume of seepaage, but it is not counted on to reduce the uplift pressure caused by the seepage.

VI. REMEDIAL ACTION: LONG-TERM MEASURES

Adding Cutoffs

Cutoffs can be added upstream and downstream of an existing concrete dam and in the abutments to treat seepage problems. Types of cutoffs include:

- Concrete cutoff walls
- Sheet pile cutoff walls
- Slurry trenches with earth/bentonite fill
- Reservoir and abutment blankets

Concrete cutoff walls have been found to be very effective for reducing seepage quantities and uplift pressures. The problems associated with concrete walls are primarily construction difficulties that may be encountered in excavating through hard but fractured rock and in saturated soils. Blasting, hand excavation, shoring, and/or dewatering may be required.

Sheet piling is used in soil foundations and can be driven to considerable depths in low to moderately dense silts, clays, and sands. When installing sheet piling in soils with a significant gravel or boulder content, serious problems can develop, such as premature refusal, driving out of interlock, and deflected pile points that do not continue straight downward.

Earth/bentonite-filled slurry trenches are often used in soil foundations. The primary disadvantages are cost and the experience level required of designers and contractors to avoid major construction difficulties.

Reservoir and abutment blankets of compacted impervious earth may be used as a cutoff measure. However, additional time and expense are required to drain an existing reservoir for installation and to obtain sufficiently detailed geotechnical data over a relatively large area. Investigation and testing for possible borrow sources of suitable materials are also required. Additional foundation and abutment seepage control measures are commonly provided as a "second line of defense" when impervious blankets are used.

Anchoring

Anchoring can be installed to stabilize weak bedding planes or joints in the foundation, or to engage a sufficient rock mass to prevent overturning or sliding of a light structure. The specific purposes of foundation anchoring include:

- Rock stabilization
- Improving resistance to damage from overtopping or environmental forces
- Improving engineering characteristics and ability to support a structure

Anchoring for such purposes is often used in conjunction with surface treatments, such as shotcrete or dental concrete.

Anchors must extend deep enough below the potential failure plane to fully develop the anchor force. Establishing the correct depth requires detailed geologic data, and geotechnical and structural expertise. Close quality control during installation is also needed.

Adding Abutment And Toe Protection

Erosion protection of abutments and toe areas of a dam is generally necessary to ensure stability during overtopping or large spill events. The removal of foundation material by flowing water during overtopping may leave voids in that protection. Voids may result in loss of toe support and reduced stability against overturning. The loss of foundation material immediately downstream of the dam may result in reduced passive resistance and a corresponding reduction in sliding resistance.

Armoring of the toe and critical downstream foundation surfaces can be accomplished by the following means:

- Placing shotcrete or anchored concrete slabs directly on the rock
- Anchoring critical foundation blocks
- Placing gabions on soil backfills or foundations to dissipate the energy of flowing water
- Grouting fractured rock foundations to form a more massive passive block
- Removing erodible materials and replacing them with concrete or gabions
- Placing riprap, including wire-pinned rock, heavy riprap, and grouted rock riprap

Table VI-2 presents a summary of abutment and toe protection materials and their uses.

Continued . . .

Adding Abutment And Toe Protection (Continued)

TABLE VI-2. ABUTMENT AND TOE PROTECTION

Protection Material	Uses
Shotcrete	Applied to surface to strengthen weak material. May be used for shallow joints and fractures.
Pressure grouting	Used to improve mass integrity if fractures or joints are deep and open.
Concrete aprons	Placed to take impact of overtopping; to span over weaker rock without undue flexing or damage to the rock or apron.
Anchor rods	Drilled and anchored into deep rock to support and hold a concrete slab when supporting rock is not sufficient to hold blocks of rock in place.
Gabions	Rock-filled wire baskets placed on soil abutments or foundations to dissipate energy of flowing water.
Wire-pinned rock	Placed on soft bedrock and soil foundations or abutments where overtopping is infrequent, of short duration, or of low impact.
Heavy rock riprap	Placed on soft bedrock and soil foundations or abutments where overtopping is of low to moderate impact and greater duration.
Grouted rock riprap	Placed on soft bedrock and soil foundations or abutments where overtopping is of low to moderate impact and greater duration. May require weepholes or pipes where uplift seepage is present.

MONITORING

Close visual and instrumentation monitoring of the performance of a modified dam should always be included as a part of any remedial measure. Monitoring provides data with which to evaluate the ongoing effectiveness of remedial actions and any changes in their performance. Once instrumentation data evaluations and visual monitoring indicate that the modification has been or is expected to be effective through the full range of anticipated loading conditions, then monitoring can be relaxed.

Continued . . .

VI. REMEDIAL ACTION: LONG-TERM MEASURES

MONITORING (Continued)

Monitoring can sometimes eliminate the need for more costly conservative remedial measures by allowing for the use of a staged approach to the mitigation of deficiencies--that is, employing less costly measures at first and adding other measures only if monitoring shows a need. However, the safety of the dam should never be jeopardized with this approach.

Monitoring prior to remedial design permits obtaining accurate design parameters and should result in a more efficient remedial design.

Instrumentation

Monitoring may involve observing existing instrumentation, installing new or supplemental instrumentation during the investigation stage to verify critical assumptions, or adding instrumentation to monitor results of remedial treatments.

Regardless of whether existing or new instrumentation is to be used as a long-term measure, a new problem-specific instrumentation plan should be prepared and implemented. Experienced specialists should be consulted regarding the adequacy of existing instrumentation and the instrumentation plan. Proper instrumentation and evaluation may identify an urgent need for remedial repairs and improve the cost effectiveness of long-term remedial measures.

For additional information on specific types of instrumentation and their purposes, you may wish to review the section of Unit II entitled "Instrumentation Data" or the TADS inspection module Instrumentation For Embankment And Concrete Dams.

EARLY WARNING SYSTEMS

For significant to high hazard dams, an early warning system should be considered. Early warning systems can range from very simple to quite sophisticated. A simple system may call for 24-hour visual monitoring and reporting on critical features from strategic observation points. A sophisticated system might include remote sensing devices such as pressure gauges, piezometers, flow meters, and stream gauges that communicate directly to officials, emergency action officials, or radio or TV stations. Warning devices such as sirens, horns, or other devices may also be employed.

An effective early warning system requires extremely close cooperation among many different governmental and nongovernmental agencies and should be tested periodically in order to evaluate performance.

For additional information on early warning systems, refer to the TADS inspection module Evaluation of Facility Emergency Preparedness.

VI. REMEDIAL ACTION: SUMMARY

SUMMARY: REMEDIAL ACTION

Unit VI provided brief descriptions of short- and long-term remedial measures that may be used when deficiencies are identified that threaten the static or seismic stability of a concrete dam.

Emergency And Temporary Measures

Emergency and temporary measures are measures that must be undertaken immediately to prevent failure of the dam or to alleviate conditions that could lead to failure of the dam. Conditions that require immediate action include:

- Erosion of foundation materials
- Leakage through concrete or foundation and abutment materials that increases with time or shows evidence of removing material
- Instability of reservoir or abutment slopes or the foundation along the toe
- Excessive settlement

Emergency and temporary measures to be considered include:

- Drawing the reservoir down
- Modifying operational procedures
- Sealing and draining cracks
- Buttressing unstable slopes
- Emergency action planning

Long-Term Measures

Long-term measures are repairs or improvements of a permanent nature that are used to correct the identified deficiencies. Long-term measures to be considered include:

- Restoring structural integrity:
  - Increasing freeboard
  - Adding weight
  - Anchoring
  - Adding thrust blocks
  - Repairing concrete

- Restoring foundation integrity:
  - Reducing seepage and uplift pressures by improving drainage systems, grouting foundations and abutments, and adding cutoffs
  - Anchoring
  - Adding abutment and toe protection

- Monioring the performance of the modified dam through visual observation and instrumentation

- Early warning systems

APPENDIX A

GLOSSARY

GLOSSARY

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

AGGREGATE - The natural sands, gravels, and crushed stones that are used in the manufacture of concrete.

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.

ARCH DAM - A concrete dam that is arched upstream so as to transmit the major part of the water load to the abutments.

BEARING CAPACITY - The maximum pressure that can be permitted on foundation rock or soil, giving consideration to all pertinent factors, with adequate safety against rupture of the rock or soil mass or movement of the foundation of such magnitude that the structure is impaired.

BEDROCK - A general term for the rock, usually solid, that underlies soil or other unconsolidated, surficial material.

BERM - A placement of fill at the toe of a slide to buttress it against further movement. Also, a step in a rock or earth cut.

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

BOND - The adhesion of concrete or mortar to other concrete layers, rock, and other surfaces.

BOND STRENGTH - Resistance to separation of concrete and other contact surfaces.

BUTTRESS DAM - A dam consisting of a watertight element supported at intervals on the downstream side by a series of buttresses. Buttress dams can take many forms, such as a flat slab, massive head buttress, or multiple arch buttress dam.

COMPRESSIVE STRENGTH - The maximum stress that a material is capable of resisting under an axial compressive load.

CONSOLIDATION - The change in volume of a rock or soil material (normally considered in the vertical direction), which results from an externally applied load causing the expulsion of fluids contained in the rock or soil pores.

GLOSSARY

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

CUTOFF WALL - A wall of impervious material, usually concrete, bentonite and earth, or steel sheet piling, constructed under a structure to reduce seepage from the reservoir beneath and adjacent to the dam.

DAM FAILURE - The uncontrolled release of impounded water. There are varying degrees of failure.

DAMPING - Resistance which reduces vibration by energy absorption.

DEAD LOAD - The constant load on the dam resulting from the mass of the concrete and other attachments.

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

DEFLECTION - Linear deviation of the structure due to the effect of loads or volumetric changes.

DEFORMATION - Alteration of shape or dimension due to stress.

DENSITY - Weight per unit volume.

DESIGN RESPONSE SPECTRA - Smooth, broad-banded spectra appropriate for specifying the level of seismic design force, or displacement, for earthquake-resistant design purposes.

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

DURABILITY - The ability of concrete to resist weathering action, chemical attack, abrasion, and other conditions of service.

EFFECTIVE PEAK GROUND ACCELERATION - That acceleration which is most closely related to structural response and to damage potential of an earthquake. It differs from, and is less than, the peak free-field ground acceleration.

ELASTIC DESIGN - Design based on a linear stress-strain relationship and elastic properties of the materials.

EPICENTER - The point on the earth's surface located vertically above the point or origin of an earthquake.

FAULT - A fracture or fracture zone in the earth crust along which there has been relative displacement of the two sides.

GLOSSARY

FOUNDATION - The portion of the valley floor that underlies and supports the dam structure.

FOUNDATION DRAINAGE SYSTEM - A line of deep holes drilled under a dam and designed to intercept and control seepage beneath the dam so as to reduce uplift pressures under the dam.

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

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

GRAVEL - Soil particles ranging in size from 1/4 inch to 3 inches.

GRAVITY DAM - A concrete dam that relies on its weight and internal strength for stability.

GROUND MOTION - A general term including all aspects of ground motion (particle acceleration, velocity, or displacement) from an earthquake or other energy source.

GROUT - A fluid material that is injected into soil, rock, concrete, or other material to seal openings, lower the permeability, and/or provide additional structural strength. There are four major types of grouting materials: chemical, cement, clay, and bitumen.

GROUT CURTAIN - A zone, created by drilling a line of holes in the foundation under a dam, into which grout is injected to reduce seepage under or around the dam.

HEEL - The junction of the upstream face of a concrete dam with the ground surface.

INSTRUMENTATION - An arrangement of devices installed into or near dams (e.g., piezometers, inclinometers, strain gauges, measurement points) that provide measurements used to evaluate the structural behavior and performance of the structure.

INTERNAL EROSION - See **PIPING**.

LIQUEFACTION - a) The process whereby soil behaves as a viscous liquid. b) A condition whereby soil undergoes continued deformation at a constant low residual stress or with low residual resistance, due to the buildup and maintenance of high-pore water pressures, which reduces the effective shear resistance to a very low value. Pore pressure buildup leading to liquefaction may be due either to static or cyclic stress applications. The possibility of its occurrence will depend on the void ratio or relative density of a cohesionless soil and the confining pressure.

LOG BOOM - A chain of logs, drums, and pontoons secured end-to-end and floating on the surface of a reservoir to control floating debris, trash, and logs.

GLOSSARY

MAGNITUDE - A measure of the strength of an earthquake, or the strain energy released by it, as determined by seismographic observations.

MAXIMUM CREDIBLE EARTHQUAKE (MCE) - The largest earthquake associated with a specific seismotectonic structure or source area within the region examined.

MODULUS OF ELASTICITY - The ratio of normal stress to strain.

MONOLITH - A section or block of the dam that is bounded by transverse contraction joints.

OPERATING BASIS EARTHQUAKE (OBE) - The earthquake, usually smaller than the MCE, associated with a specific seismotectonic structure or source area within the region examined, which reflects the level of earthquake protection desired for operational or economic reasons.

PEAK GROUND ACCELERATION (PGA) - The acceleration representing the peak acceleration of free-field vibratory ground motion; motion that is not influenced by topography or human-made structures.

PERMEABILITY - The property of a porous medium that allows water to flow through it.

PIPING - The progressive internal erosion of foundation, abutment, or embankment material.

PORE PRESSURE - The pressure of water in the voids within a mass of soil, rock, or concrete.

POROSITY - The ratio of the volume of voids to the total volume of the material.

RELIEF WELLS - Vertical wells or boreholes designed to reduce uplift pressure and collect and control seepage through or under a dam.

RESERVOIR - The body of water impounded by a dam.

RESERVOIR RIM - The boundary of the reservoir including all areas along the valley sides above and below the water surface.

RIPRAP - Broken rock or boulders placed on soft bedrock and soil foundations or abutments to provide protection from erosion due to overtopping.

ROCK - a) An aggregate of one or more minerals (e.g., granite, shale, marble). b) A body of undifferentiated mineral matter (e.g., obsidian). c) A body of solid organic material (e.g., coal).

SAND - Soil particles ranging in size from "just visible" to 1/4 inch.

GLOSSARY

SEEPAGE - The passage of water through foundation, abutment, or embankment materials.

SEISMIC STABILITY - Ability of a dam to resist the additional dynamic forces induced by ground motions of an earthquake.

SETTLEMENT - The vertical downward movement of a structure.

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

SILT - Soil particles 0.074 mm or smaller, which are nonplastic or very slightly plastic and exhibit little or no strength when air-dried.

STATIC STABILITY - Ability of a dam to resist the static forces that tend to induce sliding, overturning, or concrete deterioration and distress.

STRENGTH - The maximum stress that a material can resist without failing for any given type of loading.

STRESS - A load or force acting on a unit of area (such as pounds-per-square-inch); for example, the force per unit area acting within a rock mass.

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.

TENSILE STRENGTH - The maximum stress that a material is capable of resisting under an axial tensile load.

TOE DRAIN - A seepage control drain located along or beneath the toe, which carries internal seepage water away from the dam.

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

UPLIFT PRESSURE - Upward water pressure in the pores of a material or on the base of a structure.

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

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

APPENDIX B

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