100 Years of Embankment Dam Design and Construction in the U.S. Bureau of Reclamation

Bureau of Reclamation History Symposium
at
University of Nevada - Las Vegas
June 18-19, 2002

by

Richard Lyman Wiltshire, P.E.
Civil Engineer, Principal Designer
Geotechnical Services Division, Group 1
Technical Service Center
Bureau of Reclamation
U.S. Department of the Interior
Denver, Colorado

September 2002

©Copyright Wiltshire, Richard L., P.E.

100 Years of Embankment Dam Design and Construction in the U.S. Bureau of Reclamation

ABSTRACT

The design and construction of earthfill and rockfill embankment dams in the Western United States have evolved dramatically during the past 100 years (1902-2002). The U.S. Department of the Interior's Bureau of Reclamation (Reclamation) has played a significant role in that evolution of embankment dam engineering, construction, and dam safety during the 20th Century. There are now over 240 water-storage embankment dams in the Western United States that were designed and constructed by Reclamation. The list of civil engineers and other professionals who have helped to design and build Reclamation's embankment dams is lengthy and highly regarded.

This paper discusses Reclamation's embankment dam design and construction organizations and how they have evolved during the past century. Starting in 1902, Reclamation's embankment dam design and construction approach involved one engineer in charge of all phases of the work, from development of the project all the way through design and construction of the dam and appurtenant structures. Embankment dam design and construction were then based largely on previous experience with dams that had been successfully designed, built, and operated without failure. Since that beginning, the design of embankment dams has evolved to now include: site investigations and engineering geology; paleohydrology; evaluation of foundation conditions and treatment; laboratory investigations of foundation and borrow materials; geotechnical analysis of design criteria such as seepage, filters, slope stability, deformation, and seismic behavior; instrumentation and performance monitoring; and construction equipment, methods, and management. Reclamation's embankment dam design and construction history can be separated into five periods. Period I runs from 1902 to 1918; Period II extends from 1919 to 1933; Period III covers 1934 to 1944; Period IV includes 1945 through 1975; and Period V runs from 1976 to the Present (2002).

In summarizing Reclamation's embankment dam design and construction history, many of the notable embankment dams designed and constructed by Reclamation during each of those periods are discussed. The last 100 years have seen the design and construction of embankment dams develop from the relatively simple homogeneous or two-zone earthfill embankments designed at the beginning of the 20th Century into the extremely complex, highly analyzed, well-instrumented zoned

earthfill and/or rockfill structures that are the embankment dams of the 21st Century. A central component of the evolution of engineering of embankment dams has been the birth and maturation of geotechnical engineering as a civil engineering specialty. The evolution in construction equipment during the past 100 years is also discussed in the paper. The development of Reclamation's publications, such as the *Earth Manual*, *Design of Small Dams*, and the *Design Standards*, is also discussed. The near failure of Fontenelle Dam, the failure of Teton Dam, and the lessons learned from those events are discussed in the paper. And, the post-Teton changes in Reclamation's embankment dam designs and in the organization are discussed.

INTRODUCTION

The design and construction of earthfill and rockfill embankment dams in the Western United States and throughout the world have evolved dramatically during the past 100 years. The U.S. Bureau of Reclamation (Reclamation) has played a significant role in that evolution of embankment dam engineering, construction, and dam safety. There are now over 240 water-storage embankment dams in the Western United States that were designed and constructed by Reclamation during the 20th Century, which was the most intensive period of dam building the world has ever seen. The list of embankment dams built by Reclamation includes many of the most innovative, largest, and highest dams of their eras. The list of civil engineers and other professionals who have helped to design and build Reclamation's embankment dams is lengthy and highly regarded.

Reclamation is currently organized into five Regions across the 17 western states and the Washington and Denver Offices. The five Regions, which have performed almost all of the dam construction work, are: 1) Pacific Northwest, 2) Mid-Pacific, 3) Lower Colorado, 4) Upper Colorado, and 5) Great Plains. The Denver Office includes the Technical Service Center, the current name of the engineering organization that has performed most of the embankment dam engineering and design work.

This paper summarizes Reclamation's embankment dam design and construction history. The last 100 years have seen the design and construction of embankment dams develop from the relatively simple homogeneous or two-zone earthfill embankments designed in 1904 or 1905 into the extremely complex, highly analyzed, well-instrumented zoned earthfill and/or rockfill structures that are the embankment dams of the new millennium. This embankment dam engineering evolution has also involved the growth of several related disciplines, including engineering geology, seismology, hydrology, hydraulic engineering, instrumentation engineering, mechanical engineering, and electrical engineering. A central component of the evolution of the engineering of embankment dams has been the birth and maturation of geotechnical engineering as a civil engineering specialty. The use of computers and computer programs for the analysis and design of embankment dams became standard practice within a fairly short time after they were developed by geotechnical engineers. Another component of this evolution has been the development of larger, faster, more powerful, and more efficient earthwork construction equipment. The paper also discusses the design and construction organizations within Reclamation and how they've changed during the last 100 years. Reclamation's publication of its well-known engineering books, such as the *Earth Manual* [1][1] and the *Design of Small Dams* [2], is noted. Lastly, the successes and failures that occurred during the last 100 years of Reclamation's embankment dam design and construction history are discussed, and the lessons learned from those experiences are summarized.

In telling the story of the evolution of Reclamation's embankment dam engineering, the paper

[1] Numbers in brackets refer to References located at the end of this paper.

separates the 100-year history into five periods, which are partly based on noteworthy events such as World Wars I and II and the failure of Teton Dam in 1976. Period I runs from 1902 to 1918; Period II extends from 1919 to 1933; Period III covers 1934 to 1944; Period IV includes 1945 through 1975; and Period V runs from 1976 to the Present (2002). This paper examines the embankment dam design and construction changes that occurred during each period. Representative and remarkable/notable embankment dams from each of the five periods are discussed. A few problems, some significant, occurred during the construction and/or subsequent operation of Reclamation's embankment dams and they are also discussed. And the effects of certain developments, such as the Proctor density test procedure and the failure of Teton Dam, are discussed in the paper.

RECLAMATION'S DESIGN AND CONSTRUCTION ORGANIZATIONS

In 1902, the new U.S. Reclamation Service (Service) was organized within and was drawn from the U.S. Geological Survey's (USGS) Division of Hydrography, Hydrographic Branch, that had studied western water resources for the previous 20+ years. Frederick H. Newell, Chief of USGS's Division of Hydrography, was selected to head the new Service under USGS Director Charles D. Walcott and was titled Chief Engineer, and Arthur Powell Davis was Newell's chief assistant [3]. Based on the studies previously conducted by USGS, which had included studies of streams, watersheds, irrigable lands, and potential dam and reservoir sites throughout the West, six projects were approved for design and construction by the Secretary of the Interior in 1903. Out of 79 projects investigated, a total of 25 projects had been examined and authorized for construction by the Secretary within the first five years, and 15 of those had been started by private companies or by a group of cooperating farmers who requested the Service's help.

Period I (1902-1918)

At the beginning of Period I, each of the 16 western states (17 states after Texas was added in 1906) had at least one district under the direction of a "District Engineer", who was responsible for all Reclamation activities, including surveys, investigations, designs, and construction. For each authorized project, a qualified (civil) engineer was selected as the "Resident Engineer" and he was responsible for conducting site investigations and developing preliminary design plans on the embankment dam judged appropriate for the site. On a larger project, the Resident Engineer might have the help of an Assistant Engineer. Supervisory Service engineers, who functioned as liaison representatives of the Chief Engineer on certain projects, and consulting engineers with special skills, reviewed the preliminary plans and made project recommendations to the Secretary of the Interior. Upon the Secretary's approval, the Service was authorized to develop final plans and specifications. The early embankment dams were constructed either by contract with private contractors or by "force account" using Government forces. Both types of construction were managed/supervised by Service engineers and inspectors. Most of the dam sites were fairly remote, so construction included transportation of all necessary equipment and materials to the dam site, as well as construction of the camps and facilities required to house the construction workers.

In 1903, a permanent western headquarters office was established in Denver, Colorado, to house the engineers and assistants of the Hydrographic Branch who would facilitate the location and construction of dams, in order to avoid overcrowding in the Washington, D. C. office. The Reclamation Service became independent from the USGS in 1907, with Chief Engineer Newell becoming the Service's first Director and Davis becoming Chief Engineer. Newell reorganized the 17 states into six divisions to enhance the Service's administration of its large workload: the Central, Idaho, Northern, Pacific, Southern, and Washington Divisions. The Division boundary lines were determined by the ease of railroad travel and communication, with drainage boundaries also being considered. Each of the six Divisions was headed by a Division Engineer. Reclamation's early Project, District, and Division Engineers included such notables as: Ira W. McConnell, Raymond F. Walter, Frank E. Weymouth, Joseph B. Lippincott, Hiram N. Savage, David C. Henny, Ernest G. Hopson, Louis C. Hill, and Charles H. Swigart. Note that engineers Weymouth, Lippincott, and Hill were all elevated to Honorary Member status in the American Society of Civil Engineers (ASCE).

In 1913, the Service's hierarchy was reorganized, creating a five-member Reclamation Commission, which included: the Director of the Service, Chief Engineer, Chief Counsel, Comptroller, and Supervisor of Irrigation. In December 1914, the Chief of Construction was added as a member of the Reclamation Commission. Davis became Director of the Service in December1914 after Secretary of the Interior Franklin K. Lane removed Newell as Director and named him "Consulting Engineer." Newell finally resigned from the Service in May 1915 and became Chairman of the Civil Engineering Department at the University of Illinois. Also in May 1915, the Commission's membership was reduced to three, consolidating the Director and Chief Engineer positions with Davis as Director and Chief Engineer and retaining the Comptroller and Chief Counsel positions (which also appears to have removed the Supervisor of Irrigation and the Chief of Construction as members of the Commission). That same year, the direction of field operations was centralized at the Denver Office under the Chief of Construction. With the establishment of the Chief Engineer's Office in Denver, Reclamation's engineering design and construction management functions were centralized in the Denver Office. In 1918, the Secretary of the Interior followed Arthur P. Davis' recommendations and the top level structure of the Service was again reorganized, making the Comptroller and the Chief Counsel subordinate to the Director and Chief Engineer.

Period II (1919-1933)

In May 1920, Director and Chief Engineer Davis changed his title to Director and appointed the Chief of Construction in Denver, Frank E. Weymouth, to the Chief Engineer position. Arthur Powell Davis served as President of ASCE in 1920. On June 18, 1923, the Service became the Bureau of Reclamation headed by the Commissioner of Reclamation; Davis resigned from Reclamation the following day. David W. Davis was named Reclamation's Commissioner on July 1, 1923, quickly followed by Elwood Mead after Davis left office on April 2, 1924. Dr. Mead served as Commissioner from 1924 until his death on January 26, 1936. Reclamation's design and construction organizations remained much the same for the next 20 years. During the 1920s

and 1930s, the status of the Chief Engineer grew as Reclamation's authority was consolidated in the office of the Chief Engineer headquartered in Denver. Reclamation's various laboratories first got started in 1930 with the hydraulic model testing performed in the laboratory of the Colorado Agricultural Experiment Station in Fort Collins, Colorado. The Concrete Laboratory and the Earth Materials Laboratory were also begun in the early 1930s in the U.S. Customs House in Denver.

Period III (1934-1944)

In 1942 and 1943, Secretary of the Interior Harold Ickes reorganized Reclamation in accordance with a plan designed to: 1) decentralize the authority for work execution along regional lines, 2) limit the authority of the Chief Engineer and his staff to project design and construction, and 3) establish a "functional type" of organization with the Commissioner's authority going straight to the Regional Directors. The reorganization provided for:

> Four major branches in the Denver Office: Design and Construction under the Chief Engineer, Project Investigations, Operation and Maintenance, and Fiscal and Administrative Management. The Chief Engineer remained Reclamation's ultimate authority in the technical execution of construction projects, even though responsibility over construction in the field was now divided between the Regional Directors and the Chief Engineer.
>
> Six Regional Offices, later expanded to seven, concentrated on planning and development activities, and supervised the operation and maintenance of completed project facilities. The seven Regional Offices were located at Boise ID, Sacramento CA, Boulder City NV, Salt Lake City UT, Amarillo TX, Denver CO, and Billings MT. The Regional Directors reported directly to the Commissioner's Office.

Period IV (1945-1975)

In 1945, the Commissioner won support for his position that "the responsibility for the technical aspects of design and construction work should remain in the Chief Engineer, and therefore, authority for this work should also be vested in the Chief Engineer." This created problems for the Construction Engineers because they had two bosses: the Regional Director and the Chief Engineer. Reclamation's Denver Office included some 2,000 employees by 1948 that were scattered around the Denver metropolitan area. Reclamation's new Denver headquarters was established in 1950 as the Engineering and Research Center at the Denver Federal Center in Lakewood, located 10 miles west of downtown Denver. In 1953, during the Eisenhower Administration, the Chief Engineer's authority was upgraded and the title was changed to Assistant Commissioner and Chief Engineer. This title continued to be changed, becoming Director, Office of Design and Construction in 1963, Director, Office of Design and Construction/Chief Engineer in 1970, and Director, Office of Design and Construction in 1972.

Period V (1976-2002)

Reclamation's Teton Dam failed on June 5, 1976, killing 11 people and causing about $400 million in property damage. This failure had a profound effect on the Bureau of Reclamation. Two official panels of technical experts reviewed the probable causes of the dam's failure and released their reports in December 1976, April 1977, and January 1980. Significant recommendations by these two panels involved several areas of concern. These included: the need to establish independent dam design and construction review boards, greater documentation of design decisions, closer project supervision and oversight by design personnel, and more intensive construction and post-construction monitoring of the structures. A team was named by then Commissioner R. Keith Higginson in 1977 to review Reclamation's dam design and construction procedures, which resulted in a November 1977 reorganization that reaffirmed many of the 1943 reorganization's objectives to more clearly define the respective functions of the Denver and Washington Offices and to streamline the lines of authority and accountability. Reclamation's staff for technical review and support was established and added to the Denver Office. Since the failure of Teton Dam, and with the decrease in the authorization of new projects, the majority of the embankment dam design and construction work has involved dam safety evaluations and modifications of existing dams and appurtenant structures.

The title Director, Office of Design and Construction was changed to Assistant Commissioner for Engineering and Research in 1978. In 1979, the Bureau of Reclamation's name was briefly changed to the Water and Power Resources Service, which lasted until 1981 when the name was changed back to the Bureau of Reclamation. The Lower Missouri Region was absorbed into the Upper Missouri/Great Plains Region in 1985. The Southwest Region was abolished in 1988, splitting its area between the Upper Colorado Region and the Great Plains Region. Reclamation now has five regions: Pacific Northwest in Boise, Mid-Pacific in Sacramento, Lower Colorado in Boulder City, Upper Colorado in Salt Lake City, and Great Plains in Billings. In 1994, the Denver Office was reorganized, and the title Assistant Commissioner for Engineering and Research was changed to Director, Technical Service Center (TSC) under the Director of the Reclamation Service Center, with the latter position recently abolished. The 1994 reorganization increased the relative authority and power of the Regions and their local project and area offices, and reduced that of the TSC engineering organization.

The majority of the embankment dam design work, now mostly dam safety modifications determined necessary on existing dams, is still performed by the civil/geotechnical engineers in the TSC. The majority of the embankment dam modification construction work is done by civil engineers in the Regions and their Project and Area Offices. There are still Construction Engineers in the TSC who perform the construction management work and/or function as liaisons and provide oversight on the construction work managed by the Regions and the Project and Area Offices.

Modern Embankment Dam Design and Construction

As different cradles of civilization evolved all over the world, irrigation works and dams were basic components of their development. The earliest known design and construction of an embankment dam occurred around 2900 B.C. with the construction of Sadd el-Kafara Dam in Egypt. The early history of dams in the world includes many other countries as well, such as India, China, and Iraq. In North America, the Hohokam Indians built diversion works and canals along the Salt and Gila Rivers in southern Arizona as early as about 300 B.C. And in the Four-Corners area (Colorado, Utah, Arizona, and New Mexico), the Anasazi and Pueblo Indians constructed mud-wattle dams across streams that diverted infrequent runoff into ditches and storage reservoirs throughout the area in order to support their agricultural civilization, according to a recent study by Wright Water Engineers, Inc. of Denver, Colorado. According to *Dams and Public Safety* [4] by Robert B. Jansen (Reclamation's Director, Office of Design and Construction and Assistant Commissioner for Engineering and Research, 1977-1979), the first dam built in North America by European-Americans was built in 1623 on the Piscataqua River to operate a sawmill at South Windham, Maine. The first embankment dam was called Mill Pond Dam and was built in 1677 at Newington, Connecticut. In the far West, in early California, Old Mission Dam was built on the San Diego River in about 1770 by the Jesuits to provide water for the mission. It was composed of mortared rubble masonry and was about 5 feet high.

Starting about 1850, gold miners in California built rock-filled log-crib dams faced with wood planking that ranged up to about 125 feet in height to store water for hydraulic mining, but there were numerous failures. It should be noted that many of the early dams constructed in California during the latter half of the 19th century supplied water for mining purposes. One of the earliest notable non-mining dams in the West was San Andreas Dam, constructed on San Mateo Creek near San Francisco, California in 1870 to supply water for the city. This dam is notable because it was unknowingly built across the San Andreas fault zone. This earthfill dam was about 105 feet in height and was built using the 19th-century puddled-core technique, where the upstream and downstream shells consisted of rolled clay and the narrow core was made by manually tamping wet clay. The dam's upstream slope was 3.5:1 (horizontal:vertical, H:V) and the downstream slope was 3:1. The embankment included a cutoff trench excavated down through the alluvium and colluvium (30 to 40 feet thick) that was backfilled with a clay puddle core about 20 feet wide that was extended upward to form the central portion of the dam. The dam was subsequently raised about 12 feet in 1875 and another 6 feet in 1928. The great San Francisco earthquake of 1906 caused a horizontal strike-slip offset of about 6 to 8 feet in the left abutment, but the dam embankment was not damaged.

Across San Francisco Bay, the highest embankment dam built in the United States during the 19th-century was Chabot (Lower San Leandro) Dam, which was constructed in 1875 above San Leandro (near Oakland) on San Leandro Creek with a height of 115 feet above the streambed. Its reservoir stored residential water for the East Bay communities. It was constructed as a central-core earthfill dam, with the earthfill dumped from wagons, sprinkled, and compacted by the wagon wheels and by a herd of horses moved back and forth across the fill. The dam's cross-

section included a central foundation (cutoff) trench excavated down through foundation soils to 30 feet below the streambed. In the bottom of the cutoff trench, three parallel concrete cutoff walls were constructed 3 feet thick and 5 feet high, with about half the height (2½ feet) anchored into the foundation and half protruding up into the fill. The core zone was about 90 feet wide/thick at its bottom in the foundation trench. The embankment's upstream slope was 3:1 and the downstream slope was 2.5:1. A buttressing zone of earth and rock material was sluiced onto the downstream slope, giving the embankment a total volume of about 543,000 yd^3. In 1890, the dam was enlarged by sluicing earthfill onto the downstream slope. Subsequent raising and buttressing of the dam embankment has increased the height to 154 feet. A good source of information on the evolution of dam design and construction, including embankment dams, is *Development of Dam Engineering in the United States* [5], which includes information on six of Reclamation's embankment dams. Such was the state-of-the-art in embankment dam design and construction at Reclamation's birth.

The design of modern earthfill and rockfill embankment dams is far more complex today than was the case just 100 years ago. There are now many college courses, books, collections of professional papers, professional groups, computer programs, etc. related to the design of modern embankment dams. Most of the major unknowns and uncertainties involved with the design of embankment dams 100 years ago have been removed by the evolution of engineering experience, research, knowledge, and education. Reclamation has played a central role in that engineering evolution through its pioneering embankment designs, analyses, and soil behavior work on developing new laboratory tests and procedures for soils, development and publication of geotechnical and embankment dam engineering manuals and books, and contributions to the articles, transactions, and proceedings of engineering periodicals and professional civil engineering organizations. Some of Reclamation's learning and knowledge has come at a high price, as was the case with the 1976 failure of Teton Dam in Idaho.

In addition to the books and professional papers that now exist on modern embankment dam design and construction, several professional organizations regularly deal with and publish state-of-the-art papers on the design and construction of embankment dams and related topics. These organizations include: ASCE, the recently renamed Unites States Society on Dams (USSD, formerly the United States Committee on Large Dams, USCOLD), its worldwide parent organization, the International Commission on Large Dams (ICOLD), the International Society on Soil Mechanics and Geotechnical Engineering, and The Institution of Civil Engineers (in Great Britain).

To the lay-person, embankment dams may look like huge "piles of dirt" thrown across a valley or canyon, and it can be hard to imagine how truly complex and amazing they actually are. Most people can perceive how complex a large concrete dam, like Hoover Dam, must be with a height of 726 feet. The highest embankment dam in the world is currently Rogun Dam on the Vakhsh River in Tajikistan at a height of about 1,066 feet, and California's Oroville Dam the highest in the United States at about 770 feet. The largest embankment dam volume in the world is Tarbella Dam on the Indus River in Pakistan with a volume of about 159,000,000 yd^3, and Montana's Fort

Peck Dam is the largest in the United States with a volume of about 126,000,000 yd^3. Many of these huge embankment dams are almost as amazing in their own way as Hoover Dam.

There are many more embankment dams (currently about 72 percent) than there are concrete dams (currently about 28 percent) in the United States, out of the total of about 77,000 dams, meeting minimum dam height and reservoir volume criteria. Among several reasons, one key aspect of why embankment dams are so popular is that in general, a properly designed embankment dam can be constructed at almost any damsite, as opposed to the more stringent site limitations associated with concrete dams. A limited "picture" of the various elements that are included in the design (and construction) of a modern embankment dam is presented below. A more complete understanding can be obtained by reading publications such as Reclamation's *Design Standards No. 13 - Embankment Dams* [6] and the previously mentioned *Design of Small Dams*.

Once the need for a new dam and reservoir and a variety of other factors such as funding availability and environmental impacts have been resolved, several potential damsites are studied and investigated in sufficient detail that a conceptual design report can be developed, which includes recommendations as to the preferred damsite and the appropriate type of embankment dam and related features. Once the damsite, the type of embankment dam, and related features have been selected, more detailed studies, investigations, and analyses are conducted in order to have the information necessary to start the final design work, which concludes with the preparation of written specifications and drawings that are used as the basis for constructing the new embankment dam. The various studies, investigations, and analyses included in these design phases, which often overlap, generally include:

1) a hydrologic study of the upstream drainage basin;
2) a geologic study of the damsite and the reservoir basin, including a seismotectonic study of the area;
3) a field investigation of the foundation at the damsite and of the locally available earthfill and rockfill materials and concrete aggregates;
4) a laboratory program including testing and analysis of the soil, rockfill, and bedrock materials obtained from the damsite and the borrow area(s);
5) a conceptual design study, intended to develop and present various alternatives and their costs, and to recommend the preferred alternatives for the embankment dam, spillway, and outlet works features;
6) a final design based on the selected-alternative features, including the necessary construction specifications and drawings;
7) during construction, embankment design details often change to accommodate the changed conditions encountered; and
8) during First Filling of the reservoir and for the first few years thereafter, the performance/behavior of the foundation and/or the dam embankment may indicate the need for changes or modifications to the original design.

It should be noted that even a brief a description of how to design an embankment dam is beyond the scope of this paper. The hydrologic study of the drainage basin above the damsite develops information on the probable flood hydrology that is used to design the dam embankment and the appurtenant spillway and outlet works features. If the dam and its appurtenant features can't accommodate the flood flows resulting from the various potential storm events, the reservoir can overtop the dam embankment and cause it to fail. The geologic study develops the necessary information on the geology of the damsite and the surrounding area, which often affects the type of dam selected for design and construction. Unless the damsite's geology is properly understood, the response of the foundation to the loads imposed by a dam and reservoir may cause malfunction, leading to serious maintenance or in some cases failure of the dam. This is especially true in the event of an unexpected earthquake shaking a dam that is not designed to withstand the severity of the loading imposed on the structure. The dam, spillway, and/or outlet works can all fail because of a moderate to severe earthquake event. The field investigation and laboratory testing of the dam foundation and the embankment borrow materials accumulate and develop engineering design data on the foundation soils, bedrock, and borrow soil and rockfill materials. These field and laboratory design data are critical and must be properly collected and evaluated if dam failure is to be avoided. These design data form the basic information used in the various analyses conducted during the design of an embankment dam, including standard concerns about seepage, internal erosion/piping, settlement, static stability, seismic stability, etc. Design information on sources of sand and aggregate materials for concrete is also developed.

After the design data have been properly developed, and the various design analyses have been completed, the dam embankment's alignment, cross-section, freeboard, foundation treatment(s), material zoning, filters, drainage, camber, upstream and downstream slope protection, and instrumentation (for monitoring performance) are then determined. Computers have greatly enhanced the designer's ability to perform extremely complex analyses, as well as to create 3-dimensional models portraying the dam's configuration to ensure that all of the dam embankment's components join together properly. The written specifications and drawings that describe the details for construction of the dam are then developed. The spillway and the outlet works are similarly designed, and must be compatible with the embankment dam's design. Because of the potential public danger created by any dam and reservoir, dam design work (including that performed by Reclamation) undergoes a very high level of review, including review by boards of outside consultant experts where appropriate to ensure that our designs achieve the high quality required.

A well-known saying related to embankment dam design is that the design work is not complete until the dam's construction has been finished. And, this "construction period" should also include the first few years of a dam's performance under full reservoir loading. If the "First Filling" of a large reservoir takes 10 to 20 years to complete, then the "construction period" during which design changes and modification of the dam may be necessary could last well over 15 to 25 years. The design uncertainty during the dam's construction involves the fact that the geologic studies, the field investigation data, and the laboratory testing data actually involve a

relatively limited exposure and assessment of the dam's entire foundation and all of the earthfill materials used to construct the embankment. When the final foundation surface is completely exposed, there can easily be overburden soils and bedrock that were not encountered by any of the subsurface investigations conducted, depending on the damsite geology. And, when the borrow materials are brought to the damsite for construction of the dam embankment, some of the material may not be quite what was sampled and tested in the laboratory. The dam construction process may also be affected by the construction contractor's plans for constructing the embankment. The contractor might propose a different approach than was anticipated by the designer, such as the use of different construction equipment and the use of soil amendments to improve one of the earthfill material's characteristics (such as decreasing its permeability). Design changes during construction are most often subject to the same review process as the initial design.

The dam engineering work required in the development of the design data, the performance of analyses, the preparation of the final design, and the construction of a modern embankment dam and its appurtenant features generally involves a large number of related disciplines, including engineering geology, seismology, hydrology, civil engineering, geotechnical engineering, instrumentation engineering, structural engineering, hydraulic engineering, mechanical engineering, electrical engineering, and construction engineering. Several of the above disciplines are included as sub-disciplines or specialties within the civil engineering profession: geotechnical, structural, hydraulic, instrumentation, and construction engineering. As you can see from the "brief" description provided above, the planning, design, and construction of a modern embankment dam is a complicated process that requires the civil engineers and other professionals performing the work to have high levels of expertise and years of experience. The entire dam design and construction process can take years (sometimes tens of years) to complete.

Improvements in the size, speed, and efficiency of construction equipment during the last 100 years have played a major role in the evolution of embankment dam construction. The construction of a modern embankment dam and its appurtenant structures involves a large variety of construction equipment. A brief list of the common types of larger construction equipment typically used in constructing an embankment dam includes: backhoe, dragline, crane, articulated concrete pumper, pneumatic drill, front-end-loader, belly-dump truck, tandem end-dump truck, all-terrain haul truck, belt conveyors, water truck, bulldozer, motor grader, self-elevating scraper, excavators of all types, tamping-foot compactor (static and vibratory), sheepsfoot roller, and smooth-drum roller (static and vibratory). Construction on a large dam or at a difficult damsite may effectively utilize more efficient or unusual equipment, such as a belt conveyor system or a short railroad for hauling the borrow material to the damsite.

Reclamation's History of Embankment Dam Design and Construction

The history of Reclamation's century of embankment dam design and construction is separated into the five periods already used in describing Reclamation's design and construction organizations. Over 240 reservoir-storage embankment dam structures have been designed and

constructed by Reclamation during the past century. Some of the information presented in the following period sections on Reclamation's embankment dam design and construction history through 1958 is taken from *Development of Earth Dam Design in the Bureau of Reclamation* [7] by F. C. Walker, then Head of the Earth Dams Section, Dams Branch, Division of Design. The location map and map index of Reclamation's embankment dams are shown in **Figures 1 and 2** below and on the next page.

Figure 1

LOCATION INDEX
OF
BUREAU OF RECLAMATION EARTH-FILL DAMS

NAME OF DAM	LOCATION NO.	MAX. SECTION ON SHEET NO.
AGATE	168	17
AGENCY VALLEY	31	3
ALAMOGORDO	28	3
ALCOVA	34	3
ALTUS	55	4
AMERICAN FALLS	25	2
ANDERSON RANCH	57	4
ANGOSTURA	65	5
ANITA	40	3
ARBUCKLE	169	16
AVALON	1	1
BATU	MALAYSIA	23
BELLE FOURCHE	2	1
BIG SANDY	98	8
BLUE MESA	147	13
BOCA	45	4
BONNY	84	7
BOTTLE HOLLOW	187	18
BOX BUTTE	58	5
BOYSEN	78	6
BRANTLEY	216	22
BUCKHORN	214	22
BULL LAKE	41	3
BULLY CREEK	148	13
BUMPING LAKE	7	1
CABALLO	42	3
CACHUMA	93	7
CALAMUS	204	21
CARPINTERIA RES.	163	8
CARTER LAKE	94	7
CASCADE	66	5
CASITAS	121	9
CAUSEY	157	14
CAWKER CITY DIKE	163	15
CEDAR BLUFF	85	7
CHENEY	149	13
CHOKE CANYON	201	21
CLARK CANYON	154	14
CLE ELUM	39	3
CLEAR LAKE	8	1
COLD SPRINGS	5	1
CONCONULLY	9	1
CONTRA LOMA	179	17
CRANE PRAIRIE	53	4
CRAWFORD	143	13
CRESCENT LAKE	117	9
CURRANT CREEK	192	19
CUTTER	171	18
DAM NO. 2	110	8
DAM NO. 13	111	8
DAVIS	59	5
DAVIS CREEK	215	24
DEAVER	30	2
DEER CREEK	49	4
DEER FLAT	3	1
DEERFIELD	60	5
DIAMOND CREEK DIKE	218	24
DICKINSON	86	7
DIXON CANYON	70	6
DOWNS DIKE	164	15
DRY FALLS (SO. COULEE)	71	6
ECHO	28	3
EKLUTNA	ALASKA	16
ELEPHANT BUTTE DIKE	17	3
EMIGRANT	130	11
ENDERS	72	6
FLATIRON	87	7
FONTENELLE	155	14
FORT COBB	131	11
FOSS	132	11
FRESNO	46	4
FRUITGROWERS	50	4
FUNKS	197	20
GLEN ANNE	100	8
GLENDO	118	9
GLEN ELDER	162	15
GRANBY	67	5
GRASSY LAKE	47	4
GRAY REEF	138	12
GREAT CUT DIKE	205	23
GREEN MOUNTAIN	51	4
GUERNSEY	26	2
HAYSTACK	122	9
HEART BUTTE	79	6
HELENA VALLEY	126	10
HERON	173	18
HORSETOOTH	73	6
HOWARD PRAIRIE	133	10
HUNTINGTON NORTH	172	18
HYRUM	32	3
ISLAND PARK	43	3
JACKSON GULCH	80	6
JACKSON LAKE DAM MODIFICATION	211	23
JACKSON LAKE DIKE	12	1
JAMESTOWN	184	8
JOES VALLEY	174	15
JORDANELLE	212	23
KACHESE	10	1
KEECHELUS	16	2
KEENE CREEK	127	10
KEYHOLE	99	8
KIRWIN	105	8
LAHONTAN	13	1
LAKE ALICE	14	1
LAURO	101	8
LEMON	158	13
LEWISTON	151	13
LITTLE PANOCHE	177	16
LITTLE WOOD RIVER	133	11
LION LAKE DIKES	81	6
LONG LAKE	74	6
LOS BANOS	175	16
LOST CREEK	176	16
LOVEWELL	118	9
LOWER TWO MEDICINE	178	17
MANN CREEK	179	18
MARSHALL FORD DIKE	48	4
MARTINEZ	88	8
MARYS LAKE DIKES	69	5
MASON	180	17
McGEE CREEK	207	22
McGEE CREEK DIKE	208	22
McKAY	23	2
McMILLAN	4	1
McPHEE	206	22
MEDICINE CREEK	82	8
MEEKS CABIN	181	17
MERRITT	152	13
MIDVIEW	35	3
MINITARE	18	2
MINIDOKA	4	1
MOON LAKE	36	3
MT. ELBERT FOREBAY	194	20
NAMBE FALLS	193	19
NAVAJO	134	11
NELSON DIKES	22	2
NEWTON	61	5
NEW WADDELL	213	23
NORTH	89	7
NORTON	139	14
OCHOCO	90	7
OLYMPUS	83	6
O'NEILL FOREBAY	161	14
ORTEGA RES.	108	8
O'SULLIVAN	75	6
PACTOLA	107	8
PALMETTO BEND	198	20
PALISADES	113	9
PALO VERDE	124	10
PAONIA	137	11
PATHFINDER DIKE	11	1
PICACHO NORTH	114	9
PICACHO SOUTH	115	9
PILOT BUTTE	27	2
PINEVIEW	33	3
PISHKUN DIKES	29	3
PLATORO	91	7
PRINEVILLE	135	11
PROSSER CREEK	136	11
PUEBLO	189	19
RATTLESNAKE	103	8
RED FLEET	199	20
RED WILLOW	144	12
RIDGES BASIN	217	24
RIDGEWAY	203	21
RIFLE GAP	182	16
RUEDI	183	16
RYE PATCH	37	3
SALMON LAKE	21	2
SANFORD	153	13
SAN JACINTO RES.	64	5
SAN JUSTO DIKE	219	23
SAN JUSTO	209	23
SAN LUIS	160	14
SATANKA DIKE	87	7
SCOFIELD	62	5
SCOGGINS	191	19
SENATOR WASH	184	16
SHADEHILL	88	7
SHADOW MOUNTAIN	63	5
SHEEP CREEK	140	12
SHERBURNE LAKE	19	2
SHERMAN	141	12
SILVER JACK	166	17
SLY PARK	116	9
SODA LAKE DIKE	85	7
SOLDIER CANYON	76	6
SOLDIER CREEK	169	16
SPRING CANYON	77	6
STATELINE	200	21
SPRING CREEK DEBRIS	156	14
STAMPEDE	187	18
STARVATION	186	18
STEINAKER	142	12
STRAWBERRY	15	1
STUBBLE FIELD	112	8
SUGAR LOAF	185	17
SUGAR PINE	202	21
TAYLOR PARK	38	3
TETON	190	19
TIETON	24	2
TOA VACA	PUERTO RICO	18
TRENTON	92	7
TRINITY	196	19
TWIN BUTTES	145	12
TWIN LAKES	196	20
TWITCHELL (NAQUERO)	125	10
UNITY	44	3
VALLECITO	52	4
VEGA	129	10
WANSHIP	120	9
WASCO	136	11
WEBSTER	165	8
WHISKEYTOWN	146	12
WICKIUP	54	4
WILLARD	188	15
WILLOW CREEK-MONTANA	56	4
WILLOW CREEK-COLORADO	96	7
WINTERING	158	20

THIS DRAWING AND INDEX SUPERCEDES DRAWING No. 103 - D - 825

LOCATION INDEX
AND MAP

Figure 2

Period I (1902-1918)

As already mentioned, at Reclamation's emergence in 1902, the USGS's Division of Hydrography, Hydrographic Branch had been studying water resources in the West for about 20 years, developing data on potential reservoir and dam sites. The USGS had published reports such as *Reservoirs for Irrigation* [8], authored by James D. Schuyler in 1897. When the U.S. Reclamation Service was established and given its mission of developing western water resources, Frederick H. Newell and his nucleus of engineers were transferred from the USGS's Hydrographic Branch to the Service and they quickly started work on the design of the six projects that had been approved for design and construction by the Secretary of the Interior in 1903. Work on the additional dams and projects approved for design and construction during the next few years commenced as quickly as was possible.

What was the state-of-the-art in embankment dam design and construction in 1903? Only a few books had been published in the United States that covered the design and construction of dams, including embankment dams. The first such book was *The Design and Construction of Masonry Dams* [9] written by Edward Wegmann (Member, ASCE) in 1888, followed in 1899 by his *The Design and Construction of Dams, Including Masonry, Earth, Rockfill, Timber and Steel Structures* [10]. The third important book on dams, *Reservoirs for Irrigation, Water-Power, and Domestic Water Supply* [11], was written by James Dix Schuyler (Member, ASCE) in 1901, with a second edition in 1909 [12], which included information on the Service's Minidoka, Belle Fourche, and Cold Springs Dams. The 1909 book included chapters on: Rock-fill Dams, Hydraulic-fill Dams, Masonry Dams, Earthen Dams, Steel Dams, Reinforced Concrete Dams, Natural Reservoirs, and Miscellaneous, and included a total of 381 photos, figures, and illustrations.

The publications of several engineering, mining, and construction organizations were the primary source of information on which embankment dam designs worked or failed, and why. These publications included: Engineering News and Engineering Record (both subsequently merged to form Engineering News-Record), Mining and Scientific Press, Engineering and Mining Journal, Transactions of the American Institute of Mining Engineers, and ASCE. Service engineers such as Hiram N. Savage had already written articles on dams [13], published before the Service was created. Within a relatively short period, more books were written about dams, an increasingly important subject in the arid West. Articles about the new Service and its dams first appeared in Engineering News in 1903 and then in other publications like Engineering Record, Engineering and Construction, Irrigation Age, and Pacific Builder and Engineer shortly thereafter. Papers on the Service's dams began to appear in the Proceedings of ASCE in 1907 and of the American Society for Testing Materials in 1908 (dealing with cement and concrete work).

The Service's Chief Engineer and his initial staff of 15 (civil) engineers and related disciplines reportedly had lots of previous practical experience. Although the Denver Office was established in 1903 for the engineers and assistants from USGS, a Resident Engineer at each irrigation project was assigned to supervise the development of all phases of the project, which included

investigations, design, and construction. The project plans were reviewed by a "project board" consisting of the Resident, District, and Supervising Engineers. If warranted, one of Reclamation's technical experts or a consultant would assist on a complex or difficult project. The actual records from this early period are fairly limited. Once the reservoir storage site was examined and appeared acceptable, it was used only if the observable geological conditions were "unquestionably adequate in light of past experience." Where explorations were made, they were directed at locating a competent foundation, with little consideration given to the material overlying the good foundation. Streamflow records were either short or nonexistent. Except for critical items such as gates, cement, and reinforcing steel for concrete, materials for constructing the dam, including sand and gravel for concrete, had to be locally available due to transportation difficulties.

Reclamation's first approved project was the Truckee-Carson Project, later called the Newlands Project that was located in California and Nevada. Reclamation's first constructed dam was part of that project. Truckee River Diversion Dam located on the Truckee River in Nevada, now called Derby (Diversion) Dam, was constructed as a combination gated concrete structure and earthfill wing embankment dam. Construction of the diversion dam and canal works began under Specifications No. 1 in 1903 and was completed in June 1905. The dam was 1,331 feet long, had a structural height of 31 feet and a hydraulic height of 15 feet, contained about 37,000 yd^3 of earthfill, and had a 3:1 upstream slope and a 1.5:1 downstream slope. The Project Engineer responsible for design and construction was Leon H. Taylor. Reclamation's first completed embankment dam, whose primary purpose was to impound a water-storage reservoir, was Minidoka Dam located on the Snake River in Idaho (see **Figure 3** on next page). Its construction began in 1904 and was completed in 1906 (see **figure 4** on page after next page). It was a zoned earthfill and rockfill embankment 80 feet high that contained 257,000 yd^3 of earth and gravel fill and rockfill materials, had a crest length of 664 feet, and impounded 210,000 acre-feet of water. Minidoka Dam was designed by John H. Quinton (Member, ASCE) and was constructed under the supervision of Construction Engineer F. C. Horn.

Rolled (compacted) earthfill was generally preferred by Reclamation for embankment dam construction because of the difficulty in handling rockfill material, but hydraulic or semi-hydraulic fill construction was used in several instances. Foundation treatment varied substantially. Some of the dam foundations were excavated to bedrock, some had cutoff trenches excavated to bedrock, and some had multiple trenches. Some cutoff trenches included a concrete cutoff wall constructed into the foundation bedrock that extended up into the cutoff trench backfill. Some trenches were for drainage and some provided additional cutoffs. Two dams had pile cutoffs: one made of wood and one made of steel sheet piling; neither of them was considered very effective. Almost all of these embankment dams had one to three feet of riprap on the upstream slope.

Most of the embankment dams constructed by Reclamation during Period I were relatively small structures (by today's standards) that still took quite some time to build with the methods available at the time (Belle Fourche Dam took over 5 years). The designs for these dams, which

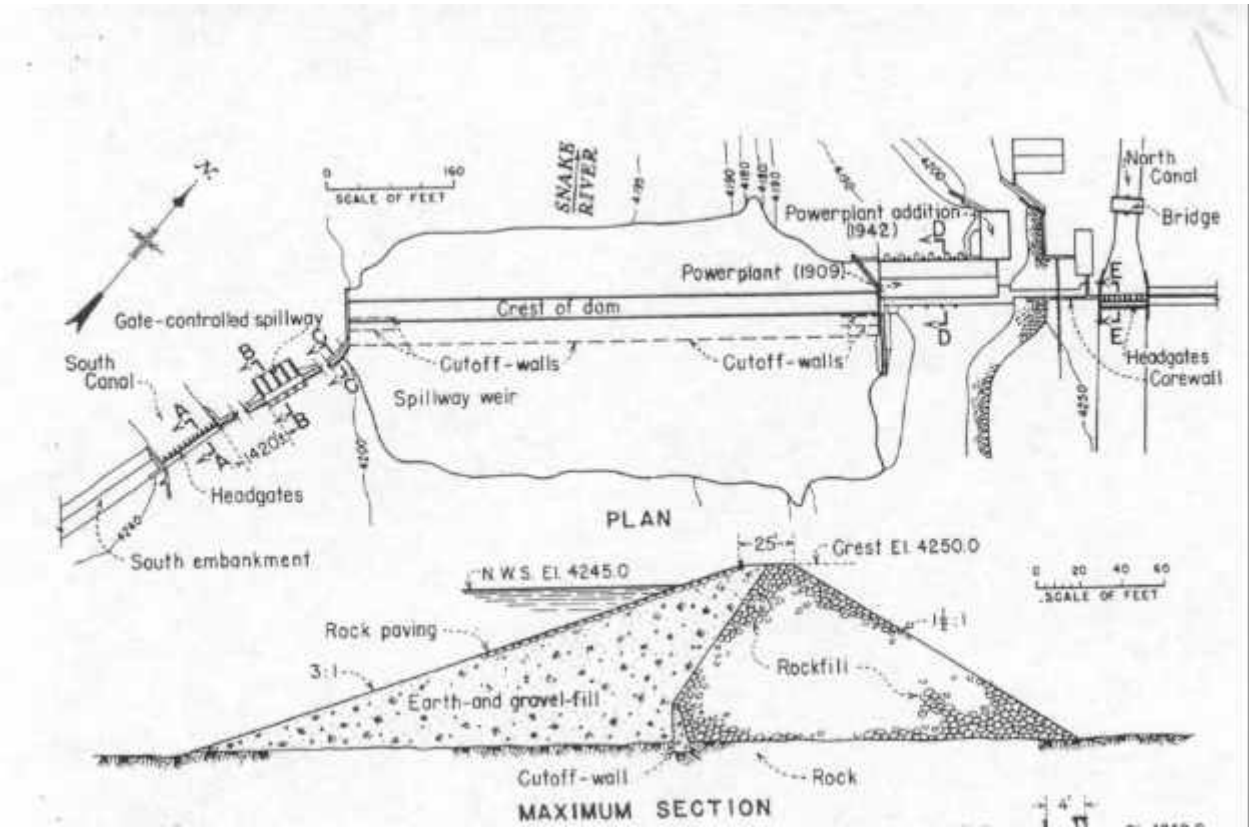

Figure 3 - Minidoka Dam Plan and Section

depended on the nature of the locally available earthfill materials (and still do today), were based on a relatively limited knowledge of geotechnical engineering and the other disciplines mentioned earlier. The design standards of that time were limited: 1) an adequate foundation to support the dam, 2) an impervious core or upstream facing, and 3) a spillway capable of passing flood flows without damage to the embankment. Data on the hydrology of the drainage basins were very limited. The geology of the damsites may have been studied and documented, but its affect on the dams to be designed and constructed was probably poorly understood. The field investigation performed at the damsite and on the earthfill borrow areas was generally limited to test pits and borings of shallow depth.

Any laboratory testing of the anticipated earthfill materials was extremely limited by today's standards since most of the tests now performed on earthfill and rockfill materials were developed during and after the 1920s. Grain size analysis was probably performed on the soils, but only of the sand, gravel, and cobble size materials, and information on the amount of clay and silt materials was not possible until later. Darcy's Law about the rate of water-flow through a soil (its permeability) was promulgated in 1856, and it dictates how and where different types earth materials (clay, silt, sand, gravel, cobbles, and rockfill) can be used in an embankment dam, which is still very relevant today. Early scientists, physicists, and engineers like Charles A.

Figure 4 - Minidoka Dam Construction

Coulomb (1773), Alexandre Collin (1846), and W. J. M Rankine (1857) developed theories about earth pressure on retaining walls and tests of the shear strength of soil materials, but there were no standardized shear-strength tests performed on soil materials or analysis of slope stability as are an integral part of embankment dam design today. The Atterberg limits tests still used today to help characterize clayey materials were developed by A. Atterberg of Germany in 1911. In 1916, K. E. Pettersson and S. Hultin developed a slope stability analysis method to analyze the failure of a quay wall in Goteborg, Sweden, but it does not appear to have been introduced to engineers in the United States until several years later. And settlement/ consolidation behavior of soil materials was not tested, although settlement benchmarks were first installed along the edges of the embankment crest at Belle Fourche Dam in 1911. Thus, the ability to develop the necessary data and to analyze an earthfill structure like an embankment dam during Period I was very limited by today's standards.

The various types of construction equipment that existed during Period I played a large role in

defining the size and height limitations placed on these early embankment dams. Excavation of foundation overburden soils (alluvium and colluvium) or borrow materials was performed by pick and shovel, horse-drawn (Fresno) scraper, dragline, and/or steam shovel. The borrow soil materials were excavated by hydraulic monitor or dredge for use in hydraulic-fill embankment dams, and by dragline and/or steam shovel for the other types of embankment dams . For relatively short distances, transportation of borrow materials to the damsite was accomplished by hydraulic pipelines or flumes in the case of hydraulic-fill dams and by horse-drawn wagons and/or scrapers for the other types of embankment dams. For longer distances, borrow materials were transported by railroads using trains of side-dump cars pulled by small "Dinkey" steam locomotives. After the earthfill material was brought to the embankment and dumped, it was spread out in relatively thin (i.e., 6-inch-thick) layers using horse-drawn drags and/or graders. Water may or may not have been added to the layers of uncompacted earthfill before compaction. Each layer of earthfill was then compacted by team and wagon travel, steel-drum rollers, concrete (cylinder) rollers, and/or steam-powered engines ("traction engines" were used at Belle Fourche Dam). The use of the sheepsfoot roller for earthfill compaction was reportedly developed around 1905, but they were not used on Reclamation's dams for a while yet. Rockfill material was either placed without compaction or was sluiced with hydraulic monitors. Period I construction by Reclamation was accomplished either by government forces or by contract with a construction company.

During this early period of embankment dam design and construction, the height of dam and the foundation geology had little affect on the design of the embankment dam section. However, the type of earthfill materials available for embankment construction had a noticeable influence. Hence, depending on the nature of the earthfill materials available in the borrow area(s), the dam embankment section was either: 1) an upstream impervious zone supported by a downstream rockfill zone, 2) an upstream impervious zone supported by a downstream gravel zone, or 3) a modified homogeneous section, which included design features that modified the homogeneous performance.

Upstream Impervious Zone Supported by Downstream Rockfill Zone

Period I embankment dams utilizing this type of cross-section included: Avalon, Clear Lake, Minidoka, and McMillan Dams and Elephant Butte Dike. Avalon and McMillan Dams, both on the Pecos River near Carlsbad, New Mexico, were actually the second or third reconstructions of earlier dams that had failed by overtopping during floods that breached both dams. Neither dam included a transition/filter zone between the earthfill and rockfill zones, which was added to later dams of this type. Avalon Dam also had a part sheet-pile, part concrete core/cutoff wall the full height of the dam. The upstream slope of these dams was typically 3:1 that was often steepened to 2:1 above the full reservoir level, and the downstream slope was typically 1.5:1. The relatively high cost of using rockfill material with the equipment then available was the reason that few of this type of embankment dam were constructed by Reclamation. The failure of several non-Reclamation dams of this type during this period probably contributed to the decision to stop building this type of dam.

Upstream Impervious Zone Supported by Downstream Gravel Zone

Period I embankment dams utilizing this type of cross-section included: Cold Springs, Lahontan, Keechelus, and Minitare Dams and Pathfinder Dike. The upstream slope of these dams was typically 3:1 and the downstream slope was typically 2:1, except for Minitare Dam. Minitare Dam had a 2.5:1 upstream slope to the full reservoir level, a 2:1 slope above that level, and a 2.5:1 downstream slope. Pathfinder Dike also had a concrete cutoff wall that extended above the reservoir level. The earthfill zone became thicker during the period, probably because gravel material was more difficult to use with the construction equipment then available, and because of the greater relative abundance of earthfill material. Although the mechanics of internal erosion (piping) of earthfill materials was not yet understood, dam designers did understand the nature of the problems potentially caused by seepage from the reservoir, as indicated by their efforts to control that seepage with defensive measures like cutoff trenches and walls. The designers also made the embankment's upstream impervious earthfill zones thicker than twice the hydraulic water-pressure head from the reservoir. Cold Springs Dam, constructed between 1907 and 1908, had a total of four zones in which the gravel content increased from 50 percent in the upstream zone to 67 percent, then 80 percent, and finally 100 percent in the downstream zone.

Modified Homogeneous Section

The remaining Period I embankment dams were of the "modified" homogeneous cross-section type, and they included: Belle Fourche, Deer Flat, Strawberry, and Sherburne Lake Dams. Except for Belle Fourche Dam, the other dams had 3:1 upstream slopes and 2:1 downstream slopes. Sherburne Lake Dam includes a vertical screened-gravel drain near the center of the embankment section, with this type of design detail being many years ahead of its time. Belle Fourche Dam had a "bold" (less conservative) embankment cross-section, probably due to its large size. The lower upstream slope is 5:1 to a berm, 2:1 above the berm to the full reservoir pool level, and 1.5:1 above that; and the upper downstream slope is 1.655:1 to a berm and drain gutter, and 2:1 below that level. At the time it was built, Belle Fourche Dam was reportedly the largest rolled earthfill dam constructed in the world; it is discussed in greater detail below. Strawberry Dam also had a reinforced concrete core wall that extended above the reservoir level.

Belle Fourche Dam

Belle Fourche Dam (locally called Orman Dam) is located on Owl Creek about 10 miles northeast of Belle Fourche, South Dakota, and was the most notable embankment dam constructed by Reclamation during Period I. The dam was constructed 115 feet high above its streambed with a crest length of 6,262 feet, an earthfill volume of 1,783,000 yd^3, impounded a 192,000 acre-foot off-stream reservoir and a water-surface area of about 8,000 acres, and was fed by a 6-mile-long canal that conveyed a maximum of 1,600 ft^3/s of water diverted by a diversion dam on the Belle Fourche River. Information on the embankment's as-built slopes is given above. The original upper slopes shown on the 1905 Belle Fourche Dam design drawings were 1:1 instead of 1.5:1 upstream and 1.75:1 instead of 1.655:1 downstream. The decision was made during construction

to flatten the upper upstream slope and flatten the upper downstream slope, moving the crest downstream (see **Figure 5** below).

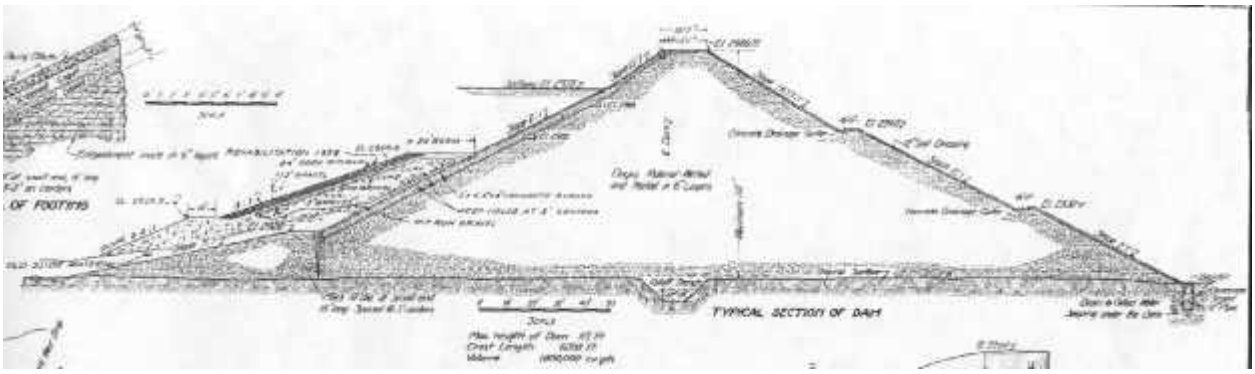

Figure 5 - Belle Fourche Dam Section

The greater steepness of the upstream slope, compared to the other embankments designed and built by the Service during Period I was an important difference. Construction under contract No. 73 awarded to Orman & Crook of Pueblo, Colorado, began in November 1905, but work was suspended in early 1908 when Orman & Crook went into bankruptcy. Construction resumed in April 1908 under a new contract with the National Surety Company of New York, who was the "bondsman" for Orman & Crook. The National Surety Company subcontracted with several private companies to perform the construction and the dam was completed on June 30, 1911. The total cost, including engineering, construction, cement, and general expenses, was about $1,299,000. An article on Belle Fourche Dam by Project Engineer Raymond F. Walter was published in Engineering Record in March 1906 [14]. A second article on the dam by Resident Engineer O. T. (Oliver) Reedy (Associate Member, ASCE) was published in Engineering Record in April 1910 [15], describing the early plans for the project and the construction to date (early 1910) on the dam and appurtenant structures. Some of the more unique or informative details related to Belle Fourche Dam's design and construction are discussed below.

In April 1904, a board consisting of Arthur P. Davis, John H. Quinton (consulting engineer from Los Angeles), and Charles H. Fitch (Supervising Engineer) examined the Belle Fourche Project and ordered detailed surveys of the irrigable areas, potential damsites, and canal alignments. Three dam sites were located and the final damsite was selected in May 1905. The dam foundation had been "thoroughly prospected" by both open test wells and by earth auger borings located every 200 feet along the dam's alignment. The embankment was founded on a "heavy compact clay," locally known as "gumbo", which overlies a soft slatey shale located 20 to 40 feet below the surface. There were occasional pockets of gravel encountered in the overburden layer. The dam embankment was constructed using the locally available clay obtained from borrow pits located upstream and at both ends of the dam. An expert "Engineer of Soils", Thomas H. Means came and tested the proposed earthfill material. Small scale experiments determined that this material needed an additional 7 percent water, by weight, for compaction to achieve the maximum density of the earthfill. Belle Fourche Dam was designed under the direction of Project Engineer

Raymond F. Walter, with the resulting plans approved by a board of engineers consisting of John H. Quinton, C. E. Wells, Charles H. Fitch, and Raymond F. Walter, resulting in a July 5, 1905, letter in which they approved the plans and specifications, recommending "that the drawings be reduced to standard size and the specifications printed in Washington and that the work be advertised as soon as possible." The 1905-era Specifications No. 56 contained a total of 37 pages and 12 drawings used to show the dam embankment, appurtenant structures, and canals. The specifications sections included topics such as: Engineer, Changes, Sanitation, Use of liquor, Embankment construction, and Measurements. During construction, several design details related to the dam's upper slopes and the appurtenant structures had to be revised. Resident Engineers Patch and Reedy were in daily to weekly contact with Project Engineer Walter during the entire period of dam construction. Visitors (mostly engineers) from as far away as South Africa and Sweden visited the dam during construction [16].

Figure 6 - Belle Fourche Dam - Cutoff Trench Construction

In August 1910, engineers from the U.S. Army Corps of Engineers (Corps) visited the dam for a few hours and subsequently informed Reclamation that they considered the dam's slopes, particularly the <u>downstream</u> slope to be excessively steep. Reclamation's engineers, including Project Engineer Walter and Chief Engineer A.P. Davis, developed the response to the Corps and provided a list of some 20 recently constructed embankment dams built with slopes steeper than at Belle Fourche Dam. They knew that the location (height) of the phreatic surface in the dam embankment would affect the slope stability of the embankment, so they decided to install some 2-inch-diameter vertical pipes to function as observation wells for monitoring the "plane of saturation." More details on these pipe observation wells are provided below.

The cutoff trench was excavated by horse-drawn "wheel scrapers" and a locomotive crane, using

a ½-yd^3 clamshell bucket, after which the trench was backfilled with compacted "select material" (see **Figure 6** on previous page). The earthfill material in the borrow area(s) was excavated by 70-ton and 75-ton steam shovels with a 2½-yd^3 bucket/dipper and was dumped into the 4-yd^3 Western side-dump cars (see **Figure 7** below). The trains of 10 to 13 side-dump cars (a total of about 60 side-dump cars were used) were pulled by 18-ton Dinkey locomotives that hauled the trains about ¾-mile to the embankment, up a maximum grade of about 4 percent onto the embankment surface. The 36-inch gage train tracks and wooden ties were moved every third layer as the embankment rose in height. Three-horse-team 1¼-yd^3 dump wagons, filled by Western graders pulled by traction engines, were also used to haul earthfill from some of the upstream borrow pits.

Figure 7 - Belle Fourche Dam
Steam Shovel, Dinkey Locomotive, and Train of Side-Dump Cars in Borrow Pit

Four-horse-team Fresno scrapers were used to move the dumped earthfill a maximum distance of 50 feet away from the tracks, and ordinary four-horse-team road graders ran over the material deposited by the scrapers to spread and level the layer (see **Figure 8** on next page). The layer of earthfill was thoroughly wetted, if necessary, using a 2-inch hose to apply water pumped up from wells or small reservoirs. If the earthfill was compacted immediately

Figure 8 - Belle Fourche Dam - Embankment Fill Construction

after being placed on the fill, little if any water needed to be applied. The specifications required that the earthfill material be placed and rolled in 6-inch layers using steam rollers weighing not less than "200 pounds per linear inch of roller rim." According to O.T. Reedy's article, one of the rollers used was a 12-ton roller with a 4-foot rolling base. According to the Belle Fourche Project History [17], an "8-ton asphalt dirt roller with smooth wheels" was also used, but it often became stuck on the slick surface of the embankment. However, most of the compaction was accomplished by four 32-horsepower 18-ton and 21-ton traction (steam) engines, with the rear wheels having been widened to create a 6-foot-wide "rolling base." The traction engines accomplished the compaction more quickly due to their greater power (see **Figure 9** on next page).

A somewhat unique feature of the construction of Belle Fourche Dam was a gap through the embankment in the vicinity of station 42+00 (note that the distance between stations 0+00 and 1+00 equals 100 feet) that was left open to pass Owl Creek flows through the damsite from the start of construction until it was quickly closed in 1909. The "Owl Creek Gap" (Gap) had side slopes a little steeper than 1.5:1. Flooding on Owl Creek occurred several times during construction, with a maximum flow of about 5,500 ft^3/s moving through the Gap. Earthfill cofferdams were constructed at the upstream and downstream ends of the Gap. Three cutoff trenches were excavated across the Gap that were backfilled with select earthfill material. A drainage system consisting of 4-inch tile pipes enclosed in screened gravel was constructed in the Gap's bottom downstream of the lower cutoff trench to collect and convey any foundation seepage to discharge into Owl Creek downstream of the dam. The Gap was closed using earthfill hauled to the dam by wagon and by train, which involved dumping the earthfill off a Howe truss bridge, and spreading and compacting the earthfill layers as rapidly as possible. The Howe truss

Figure 9 - Belle Fourche Dam - Traction Engine Hauling Dinkey Locomotive to Damsite

bridge consisted of one 100-foot center span and two 60-foot side spans built across the Gap. The Gap fill was joined to the two existing embankments by excavating the slopes of the Gap until firm material was reached. Due to the confined area, the bottom layers of earthfill were compacted by hand tampers that could exert a pressure of 1 lb/in^2, by a wooden tamper weighing about 200 pounds operated by the locomotive crane, by the small 12-ton roller, and then by the wheels of a traction engine.

Another unique feature of the dam's design was the upstream slope protection. The nearest rock quarry was located 32 miles away and the sandstone's quality was considered poor, together causing its use to be rejected. The selected upstream slope protection consisted of 8-inch-thick concrete blocks/slabs that measured 5 feet by 6½ feet, and weighed about 3,000 pounds each. A concrete footing wall was constructed at the bottom of the 2:1 slope and the bottom course of blocks rested against this wall. Along the center portion of the embankment, the concrete footing wall was buttressed by 10-inch-diameter 16-foot-long timber piles driven into the earthfill on 3-foot centers. The concrete blocks were placed on a 24-inch-thick bed of gravel using stiff-leg 3-ton-capacity traveling derricks with 25-foot masts and 50-foot booms operated by 20-horsepower hoisting engines. The blocks were moved into place with the derrick and were then levered and

hammered into place. **Figure 10** below shows the nearly-completed dam embankment from the right abutment.

Figure 10 - Belle Fourche Dam - Embankment from Right Abutment

The upstream slope protection at Belle Fourche Dam suffered some degree of damage by wave action almost every year due to the common, sustained high winds in the area and the 8-mile fetch (length) along the Owl Creek arm of the reservoir. A 4-foot-thick layer of grouted riprap was suggested in 1943 by Chief Design Engineer John L. (Jack) Savage (Honorary Member, ASCE), but World War II caused the work to be deferred. A 4-foot-thick layer of dumped rock riprap was constructed in 1976-1977, but the wave-erosion/beaching problem still persists in some areas on the upstream slope.

The downstream slope was finished by placing a 12-inch-thick layer of rich loam-soil dressing which was then "seeded with a mixture of grasses recommended by the Department of Agriculture." Concrete gutters were also placed on berms located 30 feet apart vertically, with down-slope gutters every 1,000 feet, to collect and remove runoff during heavy rainstorms.

The dam included two canal outlet works, each one well above the old Owl Creek channel, and a waste weir (spillway) at the left (north) end of the embankment. Downstream of the weir structure, the spillway channel was earth lined below which it was concrete lined. Ensign-type balanced valves were installed on the canal outlet works in 1910 and 1911. Two 58-inch valves were installed at the upstream end of the North Canal outlet works conduit and one 58-inch valve was installed at the upstream end of the South Canal outlet works conduit.

During the summer of 1910, after the reservoir had reached a maximum elevation of about 2930 feet, seepage began to surface downstream of the dam where the ground is at about elevation 2910. Borings were driven to investigate the cause and source of the seepage, which indicated a strata of disintegrated shale and gravel about 10 feet below the surface. The engineers had known about this layer of gravel, but thought is was 30 to 40 feet below the ground surface. Supervising Engineer David C. Henny of Portland, Oregon, had been brought in as a "consulting engineer" during much of the work on the dam, and he was again consulted on the seepage problem. A drainage system was advised, designed, and constructed along the downstream toe of the embankment in November and December 1910. This drainage system consisted of a trench excavated about 3 feet wide and up to 17 feet deep between stations 26+00 and 41+00 (1,500 feet), with 14-inch-diameter "telephone pole auger" wells drilled in the bottom of the trench that were backfilled with coarse screened gravel, covered by fine screened gravel and then pit-run gravel. A 12-inch-diameter vitrified clay tile pipe was placed with open joints and surrounded by coarse screened gravel (1-inch to 2-inch) and by fine screened gravel (¼-inch to 1-inch) surrounding the coarse gravel in the bottom of the trench, which was then covered with unscreened gravel and regular backfill. Manholes were constructed at several locations along the toe drain- using 2-foot-diameter vitrified clay pipe. The outflow from the drainage system reached a maximum of 45 to 50+ gal/min, which varied with the reservoir water surface elevation. The flow from this drainage system has been monitored ever since, and constitutes the longest continuous monitoring performed on one of Reclamation's embankment dams.

In late 1911, a series of 2-inch-diameter open-end pipe (observation) "wells" were installed in the embankment in the vicinity of stations 37+00 and 38+00 to determine the "plane of saturation" (phreatic surface) and to obtain data on its movements with reservoir fluctuations. A wash-boring apparatus was used to drill the holes into which the pipes were installed; 34 wells were constructed, ranging in depth from 10 to 90 feet. These were the first "instruments" installed in a Reclamation embankment dam for the purpose of monitoring the porewater pressures in the dam and/or foundation. A few of these observation wells are still monitored, making them the longest continuously monitored instruments of that type. Their rate of response to reservoir fluctuation is very slow (about a 2-year lag time) due to the relatively large diameter of the 2-inch pipes and the very low flow rate (permeability) of the seepage percolating through the gumbo-clay embankment. Also in 1911, a set of iron benchmarks was installed every 300 feet along the embankment crest to monitor its settlement, also the first of that type of instrumentation installed on a Reclamation dam. Belle Fourche Dam was quickly turned into the most instrumented embankment dam built by Reclamation between 1902 and 1911.

The 90-year-long performance of Belle Fourche Dam has been quite an interesting story. The concrete paving blocks protecting the upstream slope have suffered storm damage fairly frequently, which is why that type of slope protection was not used after the construction of Minitare Dam in 1915. In 1928, after 17 years of acceptable embankment performance, parallel cracks several hundred feet long occurred on the embankment crest between stations 27+00 and 31+00, and they occurred close to the upstream slope. This lead to an investigation and exploration shafts; the cracks were up to 3 inches wide and up to 12 feet deep. The resulting

judgement was that drying out of the embankment was the cause. Other cracks had also been reported in the vicinity of station 39+00 to 46+00. Then on August 2, 1931, after a fairly rapid drought-caused reservoir drawdown of 27 feet in 60 days, part of the upstream slope failed, resulting in a slump about 610 feet long between stations 40+50 and 46+60. The slide mass averaged a thickness of 9 to 10 feet and extended from about elevation 2962 down to the base of the 2:1 slope at elevation 2920. Several factors contributed to this slide, but the steepness of the upstream slope, the (low) shear strength of the as-constructed "gumbo" clay embankment material, the low permeability of the "gumbo" clay material, and the rapid reservoir drawdown were the primary factors that caused the failure.

The slope failure was quickly examined by Reclamation's engineers, including Chief Design Engineer Savage on August 12th. Plans for reconstruction of the upstream slope were agreed upon. On August 24th, a ¾-yd^3 dragline began building an access ramp into the slide and began to remove the concrete blocks. A total of 20,320 yd^3 of the slumped embankment material and gravel bedding was excavated by a larger dragline with a 50-foot boom and a 1¾-yd^3 bucket, making sure to dig at least 1 to 2 feet below the "lowest slip plane," and placing the material in stockpiles to one side for reuse. The embankment was then rebuilt by several pieces of equipment. The larger dragline picked up a half-bucket of gravel, then filled the bucket with stockpiled embankment material, and dumped the material into the excavation where it was hauled and spread in 6-inch layers by Caterpillar tractors pulling Fresno scrapers. These layers were then compacted by rollers pulled the Caterpillar tractors. The initial attempts to use concrete rollers for compaction encountered difficulty when the roughness of the roller prevented it from being properly cleaned. An "iron mule" loaded with one yard of gravel was tried, but it was too slow. They then tried an old printing press roller, for which they had to make a pulling device, and filled the roller with concrete. This smooth roller allowed the use of cleaning scrapers and it worked well pulled by a "Fifteen" (horsepower) Caterpillar tractor. A total of eight Caterpillar tractors were used, ranging in size from fifteen to forty horsepower. The most effective "dirt mover" was a "Thirty" Caterpillar tractor pulling a 1½-yd^3 Fresno scraper. Up to three working shifts were used due to the approach of winter. Once the embankment was rebuilt, the gravel bedding was rebuilt and the concrete paving blocks were placed back on the upstream slope.

After the completion of this reconstruction, Reclamation proceeded during the remainder of the 1930s to drill, sample, install piezometers (for monitoring water pressure) in the dam embankment and foundation, and then conduct a laboratory investigation of the Belle Fourche Dam embankment material in one of the most comprehensive laboratory investigations conducted up to that time. That work was followed by a (then) state-of-the-art analysis of the upstream slope stability. Finally, in 1939, a 25-foot-wide earthfill berm was constructed to improve the stability by buttressing the upstream slope. The berm sloped at 3:1 and included a 3-foot-thick layer of well-graded ¼-inch to 3-inch gravel that was placed against the existing dam embankment to provide drainage. The berm included earthfill material similar to the original embankment material, but it was enclosed in gravel for drainage. The earthfill material was placed in 6-inch lifts and was compacted by 12 passes of a tamping roller. The tamping rollers were to

be configured such that they had one ball foot or knob for each square foot, a knob end area between 5 and 7 in^2, produced a knob pressure of not less than 300 lb/in^2, and were equipped with roller cleaners. The berm was surfaced with 24 inches of riprap placed on 12-inches of gravel bedding. Weep holes were also drilled on 5-foot centers through the concrete paving slabs for drainage purposes. The embankment section shown in **Figure 5** includes this upstream berm. The concrete paving slabs on the upstream slope continued to be damaged by wave action, and in 1976-1977, the upper portion of the upstream slope was rebuilt to provide 4 feet of riprap slope protection on a 2.33:1 slope from the top of the 1939 berm (elevation 2950) to the embankment crest (elevation 2990). Longitudinal cracks have continued to appear on the dam crest into the 1990s, and the rate of reservoir drawdown continues to be carefully controlled in order to prevent further drawdown-induced slope instability.

Belle Fourche Dam is a truly amazing and unique early embankment dam in Reclamation's history. ASCE designated Belle Fourche Dam a National Historic Civil Engineering Landmark in 1988, and (somewhat surprisingly) it is Reclamation's only embankment dam so honored. Many of the design details and construction procedures developed and utilized at Belle Fourche Dam starting 97 years ago are still used by Reclamation engineers today, especially some of the innovative design and construction concepts.

Period II (1919-1933)

Reclamation engineers had helped advance the state-of-the-art in embankment dam design and construction during Period I. Reclamation's reputation grew as the numbers of its successful projects increased throughout the West. Reclamation received more and more publicity in the articles and papers published in western newspapers, magazines, and professional journals to which Reclamation's engineers contributed their experience, innovations, and new design ideas. Reclamation's engineering design groups had been centralized and were better organized in the Denver Office, and they produced designs for new projects and dams at a high rate. Respected civil engineers like J. L. Savage, who had started his career with Reclamation on the Minidoka Project in 1903, had joined the new Denver Office staff as a Design Engineer in 1916 and was subsequently promoted to Chief Design Engineer in February 1928. The Chief Engineers during Period II were Arthur P. Davis (also serving as Director of the Service until 1923), Frank E. Weymouth, and Raymond F. Walter.

The embankment dams designed and constructed during Period II were larger and the designs were more varied. Consultants were used extensively during Period II, although the list of dams constructed during this period is fairly small. Most of them were built with homogeneous sections, had little foundation treatment of note, and generally had 3:1 upstream and 2:1 downstream slopes. Early in this period, the 40-foot-high Salmon Lake Dam was constructed between 1919 and 1923 on Salmon Creek as part of the Okanogan Project in Washington state. It was Reclamation's first embankment dam that utilized a central impervious (sandy loam) core and a flattened downstream toe or "tail" with 5:1 and 10:1 slopes. It was also the first dam to be constructed on a "questionable" foundation (sand and clay of unknown depth). The base of the

impervious core was widened, and in the bottom of the 8-foot-wide cutoff trench located 25 feet upstream of the dam crest, Wakefield sheet piling 38 feet long was driven into the foundation with part of the sheet piles extending up into the core. Note that these embankment design changes were included on a relatively small dam.

Several other notable embankment dams were designed and constructed during Period II. These included: Sherburne Lake, Tieton, McKay, Guernsey, American Falls, Echo, and Cle Elum Dams. Most of the embankment dams constructed during Period II were compacted earthfill structures, with some semi-hydraulic fill dams built too, such as Tieton Dam. Most of them were built on rock foundations that required the excavation of the overburden soils. Some of these dams included reinforced concrete core walls the full height of the reservoir, such as at Tieton and American Falls Dams. Sherburne Lake Dam, completed in 1921, included a vertical zone of screened gravel located beneath the downstream edge of the crest intended to prevent saturation of the downstream embankment material. This was one of the earliest uses of a "chimney drain" inside an embankment dam to control the phreatic surface and porewater pressures.

Tieton Dam, completed in 1925 with a maximum height of 185 feet above the streambed, was the highest embankment dam built by Reclamation during Period II. It was the first Reclamation dam designed on the basis of a stability analysis, and the soil's shear strength characteristics were assumed on the basis of the material's angle of repose. A concrete core wall 10 feet thick was excavated down a maximum of 134 feet through river-channel deposits and 10 feet into bedrock. This foundation wall was constructed by mining out vertical shafts driven to bedrock and horizontal side drifts, forming a wall within the foundation. The core wall foundation was also pressure grouted using five holes each 22 feet deep in one of the first such applications (the maximum grout take was only one sack per foot). Grout is generally a mixture of cement and water, and possibly sand, bentonite, and other materials. According to *Design of Small Dams* (p. 195), "Foundation grouting is a process of injecting under pressure a fluid sealing material into the underlying formations through specially drilled holes to seal off or fill joints, fractures, fissures, bedding planes, cavities, or other openings." The Tieton Dam embankment included a puddled-clay core one-third the thickness of the hydraulic head constructed against the upstream side of the concrete core wall. The remainder of the dam was constructed using the semi-hydraulic fill method in which the earthfill is dumped at the upstream or downstream embankment shoulder and is sluiced with jets of water, washing the fines into the center pool.

McKay Dam, completed in 1926 with a maximum height of 160 feet above the streambed, rested almost entirely on bedrock and was constructed of compacted sand and gravel. The upstream slope at 1.75:1 is the steepest ever constructed on one of Reclamation's embankment dams and was covered with a monolithic concrete slab tied to bedrock with a concrete cutoff. Three cutoff walls were constructed across McKay Dam's foundation contact, and the foundation beneath each of the walls was grouted. Steps were cast into the upper part of the upstream concrete facing to break up the wave runup (unlike the smooth concrete-panel facing at Belle Fourche Dam). The concrete facing was very hard to construct and the construction engineer advised against using that design again.

Guernsey Dam, completed in 1927 with a maximum height of 105 feet above the streambed, rested on a pervious foundation of unknown depth. Because of the foundation, the embankment section included an upstream "blanket" and a large downstream rockfill. The central portion of the embankment included an inclined impervious core zone confined by zones of sluiced sand and gravel located upstream and downstream of the core. This was the last hydraulic fill embankment constructed by Reclamation. A new concept used at Guernsey Dam was the incorporation of the upstream cofferdam into the embankment section. A partial cutoff trench was excavated and backfilled with the impervious earthfill.

American Falls Dam, also completed in 1927 with a maximum height of 75 feet above the streambed, was a combination concrete gravity and earthfill structure. The bedrock foundation beneath its reinforced concrete core wall was grouted.

Echo Dam, completed in 1931 with a maximum height of 130 feet above streambed, was another zoned embankment. The central core consisted of compacted clay, silt, sand, and gravel; the zones upstream and downstream of the core consisted of sand and gravel; and the downstream toe zone consisted of conglomerate rockfill rolled in 12-inch layers. The excavated cutoff trench was about 25 feet deep to bedrock and included a concrete cutoff wall. The cutoff trench was located well upstream of the central core and was connected to it by a thick blanket of the compacted core material. The earthfill materials were hauled to the damsite using gasoline-powered trucks, the first such use on one of Reclamation's embankment dams. Compaction of the embankment materials was accomplished using a sheepsfoot-type tamping roller for the first time on a Reclamation dam. The sheepsfoot tamping roller was an important development in the evolution of earthfill compaction because of the kneading action produced by the steel knobs or "feet" fabricated around the roller drum. Water and/or sand were usually placed inside the steel drum to increase its weight and thereby the amount of stress applied by the ends of the feet during compaction.

Cle Elum Dam, completed in 1933 with a maximum height of 135 feet above the streambed, was the first instance in which a sheepsfoot tamping roller was specified to be used for embankment compaction (it was used, but was not specified on Echo Dam). Cle Elum Dam was the last dam designed using just empirical rules and the last one constructed without earthfill testing to verify the quality of the as-built earthfill materials, to evaluate construction practices, and to confirm design assumptions.

Dams generally put more people at risk than other type of civil works structure. Dam failures tend to be catastrophic, which causes them to be studied very thoroughly to try to explain <u>why</u> the failure occurred and to avoid repeating any mistakes. The dramatic failures of dams like St. Francis Dam at about midnight on March 12, 1928, near Los Angeles, California tended to produce important changes in the practice of dam engineering. By the end of 1929, several states had enacted laws placing the construction and maintenance of non-Federal dams that imperil the lives and property of others under the supervision and control of the State engineer or other authorized official. With embankment dams, the need to explain why a dam failed when the same

basic design had worked elsewhere was a major concern to all civil engineers, as well as the general public. As civil engineering evolved, the increasing knowledge of the engineering design of certain materials (such as wood, steel, and concrete) that are used in constructing civil structures (such as buildings, bridges, and dams) generally improved the overall record with respect to reducing the incidence of structural failure. However, the failure rate with respect to embankment dams did not seem to keep pace with the evolution of those other civil engineering structures, and remained of great concern into the 1920s and 1930s. In general, Reclamation had a very good record with respect to its embankment dams. However, Reclamation's record was not perfect, as evidenced by the rapid drawdown failure of the upstream slope of Belle Fourche Dam in August 1931. While this slumping of the upstream slope material did not breach the dam or release the reservoir, the steep slope did become unstable and it did fail.

In the years just after World War I, several European engineers began to specialize in the mechanics of soil and rock materials, and thereby began the field that has become geotechnical engineering. Dr. Karl Terzaghi (Honorary Member, ASCE) is generally considered the father of soil mechanics (geotechnical engineering). According to *Karl Terzaghi - The Engineer as Artist* by Prof. Richard E. Goodman [18], Karl Terzaghi graduated from the Technical University of Graz in 1900 with a degree in mechanical engineering, having resisted his grandfather's civil engineering profession. However, after a short stint working as a mechanical engineer, Karl Terzaghi switched and began his life-long career in civil engineering. After receiving his Doctor of Technical Sciences degree from the Technical University of Graz in 1912, Dr. Terzaghi visited the United States for the next two years. He quickly found his way to a meeting with Service Director F.H. Newell and immediately began an extensive tour of Reclamation projects and dams then under construction. Back in Europe, Dr. Terzaghi began to study the mechanics of soils toward the end of World War I in 1917, working on the problem of earth pressure against retaining walls that had been worked on earlier by Coulomb and Rankine. Dr. Terzaghi's work (in German) was first summarized (in English) in Engineering News Record in 1920, which wrote an editorial preface declaring that characterizing earth as an engineering material is "the outstanding research problem in civil engineering" and that Terzaghi's article "heralds the opening of an avenue of progress." He completed the manuscript for *Erdbaumechanik* (Principles of Soil Mechanics) in April 1924 and, after it was translated from German to English, it was circulated widely in the United States by John R. Freeman (Honorary Member, ASCE). The Massachusetts Institute of Technology quickly offered Dr. Terzaghi the opportunity to develop a graduate course in foundations and soil mechanics. Because of Prof. Terzaghi's background and expertise in geology, the "marriage" of geotechnical engineering and geology has been one of his more important achievements. Prof. Terzaghi continued to lead in the development of the new field of soil mechanics and foundation engineering in the United States, with a continued special interest in dams until his death in 1963. (In his memory, Mission Dam in British Columbia, Canada was renamed Terzaghi Dam in 1965.) Briefly described, thus began what is now geotechnical engineering. The birth of geotechnical engineering as it relates to embankment dams "arrived" at ICOLD's First Congress on Large Dams meeting in 1933 at Stockholm, Sweden, which was quickly followed by ICOLD's Second Congress on Large Dams meeting in 1936 at Washington, D.C. Reclamation engineers participated in both of these meetings, including Commissioner

Mead and Chief Design Engineer Savage.

Reclamation's first engineering publication, entitled *High-Pressure Reservoir Outlets - A Report on Bureau of Reclamation Installations* by J. M. Gaylord, Electrical Engineer, and J. L. Savage, Designing Engineer, was published in 1923 [19]. This book of 179 pages included information and reproductions of drawings on the outlet works designed for and constructed at many Reclamation dams, including Minidoka, Belle Fourche, Strawberry, Lahontan, Minitare, Jackson Lake, Sherburne Lake, and McDonald Dams (McDonald Dam was designed and constructed by the Service under an agreement with Interior's Indian Affairs Office). A second engineering publication, entitled *Dams and Control Works*, was published by Reclamation in 1929 [20]. This book of 164 pages included information written by Reclamation engineers on various diversion and storage dams, including Tieton, McKay, Guernsey, American Falls, and Echo Dams. A section of miscellaneous articles presented information on topics such as: Corewalls for Earth and Rockfill Dams, and Design and Construction of Small Earth Dams. And the Appendix included a reprint of the recent specifications on Echo Dam. Included in the article on Design and Construction of Small Earth Dams was a material placement recommendation for two-zone embankment dams. This recommendation called for placement of the selected water-tight material in the upstream portion of the dam, and of the heavy, stable, free draining material such as sand, gravel, and stone in the downstream portion, distributed such that the coarser material was placed on the downstream slope, changing gradually to the finer and more claylike material as the impervious material in the upstream portion of the dam was reached. The importance of the proper placement of soils with fine-grained vs. coarse-grained gradations within a dam embankment became much better understood subsequently in the 1940s and 1950s.

Field and laboratory testing of soil and rock materials also began to emerge during the 1920s and early 1930s. In addition to the pioneering soil mechanics work by Dr. Terzaghi on topics such as soil permeability, others contributed greatly to the evolution of soil and rock testing in the attempt to characterize these materials. Reclamation's Earth Materials Laboratory was established in Denver at the U.S. Customs House in the fall of 1933. The primary duties of the new Earth Materials Laboratory "were to determine the characteristics of proposed embankment and foundation soils, to work with the design section in planning field control tests on the foundation and compacted embankment, and to train construction inspectors in the test procedure" [21]. While the subject of soil compaction and optimum moisture content had been written about as early as 1907, Ralph R. Proctor developed a soil test procedure in 1933 that established the principles of soil compaction and moisture content and their application. A four-article series was published by Engineering News Record beginning on August 31, 1933. Proctor's compaction control test standard was quickly adopted by every engineer and organization involved with embankment dams, which was a major milestone in the history of embankment dam design and construction. In addition to performing Proctor's density test, Reclamation's Earth Materials Laboratory used or developed a variety of soil testing equipment and procedures, which included mechanical (grain size) analysis, penetration resistance (on compaction specimens), percolation and settlement, consolidation, shear strength, specific gravity, and soluble solids. The laboratory also began to conduct studies and experimentation on different methods of compaction, on the

percolation rates in different soils, on porewater pressure movement through different soils, and on consolidation rates of different soils. The rapid drawdown failure of the upstream slope at Belle Fourche Dam in 1931 indicated that there was still a lot for Reclamation's engineers to learn about soil mechanics and earthfill embankments.

As Period II began, the World War I advances in mechanized equipment such as tanks and trucks lead to the post-war development of new construction equipment. Gasoline engines were now used to power 5-ton trucks for hauling earthfill materials more quickly and with greater economy. The new 15-horsepower Caterpillar tractor was introduced and could be used to pull a roller for earthfill compaction, a Fresno scraper for moving earthfill, or a bulldozer for excavating and moving earth materials. Further development of larger-sized engines lead to more powerful Caterpillar tractors and other construction equipment during Period II. As discussed on Echo and Cle Elum Dams, the use of sheepsfoot tamping rollers for compacting earthfill materials on Reclamation's embankment dams began in the late 1920s and early 1930s.

Period III (1934-1944)

Reclamation's state-of-the-practice in embankment dam design and construction at the beginning of Period III had developed to a fairly high degree of sophistication. Reclamation's projects and dams were often written about in publications like Engineering News-Record and its engineers' papers were often published in ASCE's Transactions. Reclamation's reputation and those of its engineers were well established in the West and the United States. Reclamation's evolution in concrete dams peaked during Period III with the design and construction of Hoover Dam. While the concrete dams received more notice nationally and worldwide, Reclamation designed and constructed several milestone embankment dams during Period III.

Reclamation's centralized engineering design and construction organization and the Chief Engineer in the Denver Office were well established and empowered. Reclamation's Chief Engineers during Period III were Raymond F. Walter (mentioned earlier under Period II) and Sinclair O. Harper, and J. L. Savage remained the Chief Design Engineer during the entire period.

The embankment dams designed and constructed during Period III involved some revolutionary changes and they were larger and more numerous than ever before. At about the same time, testing of earth materials, construction testing for compaction and moisture control, and engineering design specialization all became part of Reclamation's embankment dam design and construction process. The installation of performance monitoring instruments in Reclamation's embankment dams became standard procedure during this period.

Data from laboratory testing, construction control testing, and performance measurements obtained on Reclamation's embankment dams were collected and analyzed by the specialized embankment dam design group, which determined that soil as a construction material was extremely variable and very sensitive. The data also indicated that the performance characteristics of many types of ordinary soil could not be adequately defined by the existing tests and

procedures. Hence, the earthfill construction practices then in use would not necessarily produce the desired consistent performance. While attempting to solve these concerns and problems, the successful empirical design and construction practices historically used with success by Reclamation continued to be followed. Government regulations covering concerns such as working hours, transportation of equipment, safety, and wage rates became part of the process.

Many notable embankment dams were designed and constructed by Reclamation during Period III. These included: Hyrum, Pineview, Agency Valley, Rye Patch, Taylor Park, Moon Lake, Alcova, Caballo, Bull Lake, Midview, Fresno, Green Mountain, Deer Creek, Vallecito, and Anderson Ranch Dams (the latter dam wasn't actually completed until 1947). All of these embankment dams were constructed as compacted earthfill structures. The dams had upstream slopes ranging from 3:1 to 3.5:1 with flatter slopes at the (upstream) toe where material needed to be wasted, and had downstream slopes ranging from 2:1 to 2.5:1, similarly with flatter slopes at the (downstream) toe. These dams were built on a variety of foundations; almost all of them included a cutoff trench excavated down through the overburden soils to bedrock and quite a few of them included concrete cutoff walls in the bottom of the cutoff trench. The cutoff trenches moved toward the center of the dam. The rock(fill) material produced from required excavations, that was unsuitable for use as upstream riprap, was often placed on the downstream slope of the embankment.

Pineview Dam, completed in 1936 with an initial maximum height of about 55 feet above streambed, included a steel sheet pile cutoff in the foundation, which was later determined to be ineffective, causing little if any porewater pressure drop in the seepage percolating downstream. The dam's crest was raised about 29 feet in 1955.

Taylor Park Dam, completed in 1937 with a maximum height of 167 feet above the streambed, was constructed as an embankment dam at a good concrete damsite because of its remoteness. Comparative cost estimates were developed for both types of dam, and they indicated little difference in cost. Contractors were allowed to submit alternative bids, and an embankment dam was the low bid. This reportedly indicated that earthfill construction had developed to the point where it could be cost competitive with concrete dam construction at a damsite suited either type of dam. A large rockfill zone mantles the downstream slope.

Alcova Dam, completed in 1938 with a maximum height of 185 feet above the streambed, was a fairly complex embankment dam. The foundation consisted of sedimentary rock dipping downstream that had quite different permeabilities, artesian pressure in one bedrock layer, and hot sulfurous groundwater. An extensive "U"-shaped grout curtain was constructed in the foundation and up the abutments to control seepage and uplift. A concrete gallery was constructed on top of the excavated bedrock to provide access for drilling drain holes and to perform additional foundation grouting if the need arose. Alcova dam was thoroughly instrumented with the new hydrostatic pressure indicators at three sections of the embankment to monitor porewater pressures. A large rockfill zone mantled the downstream slope.

Fresno Dam, completed in 1939 with a maximum height of 75 feet above the streambed, was built on a very soft foundation of questionable strength. Consolidation of the foundation and settlement of the embankment became major problems as construction progressed. A theoretical approach and the results of plate bearing tests of the foundation were used to estimate the total settlement, which was estimated to be relatively minor. However, the actual settlement has been in excess of 8 feet, about half of which occurred during construction. The base of the dam embankment was widened, primarily to avoid abrupt changes in the stress in the foundation and to distribute the load from the embankment. Piezometers were installed in the embankment for the first time to monitor the development of construction porewater pressures in the earthfill. The control of embankment compaction and earthfill moisture content proved to be effective in controlling the earthfill porewater pressures.

Green Mountain Dam, completed in 1943 with a maximum height of 274 feet above the streambed, was the highest embankment dam yet built by Reclamation. Collectively, Green Mountain, Deer Creek and Vallecito Dams marked Reclamation's initial use of geological data in formulating the embankment dam's design. The alignment of Green Mountain Dam was shifted downstream to avoid an old landslide in the left abutment. The upstream foundation was excavated to bedrock to remove potentially unstable foundation material. Shale bedrock unexpectedly deteriorated rapidly on exposure to the air, which was addressed by spraying an asphalt coating on the shale immediately after it was cleaned off. This procedure became standard practice on Reclamation dams whenever shale is encountered. The borrow material was processed to remove the cobble-size (plus 3-inch) particles from the earthfill used to construct the embankment. The compacted earthfill at Green Mountain Dam achieved the highest dry density yet at 132 lb/ft^3. Even at this high density, construction-induced porewater pressures in the embankment caused by the weight of the fill were excessive. Studies were begun to discover what could be done to avoid this effect, with the finding that slight reductions in moisture content in the earthfill caused a marked reduction in the earthfill porewater pressures. Construction practices on Reclamation's embankment dams were changed accordingly.

Anderson Ranch Dam, started in 1941 and completed in 1947 with a maximum height of 344 feet above the streambed and with a cutoff trench excavated a maximum of 112 feet to bedrock, set a new record as the World's highest embankment dam. The scheme developed on Green Mountain Dam to carefully control the earthfill moisture content to avoid excessively high porewater pressures was followed on Anderson Ranch Dam, but it wasn't until near the end of construction that the moisture content control effort effectively controlled the porewater pressures. The designed upstream and downstream slopes gradually flatten from crest to toe, going from 3:1 to 3.5:1 on the upstream slope and from 2:1 to 2.5:1 to 8:1 on the downstream slope. This was done in an attempt to balance the cost savings from minimizing the embankment volume (steeper slopes) vs. the need to maintain adequate slope stability (flatter slopes). In 1941, the design of the embankment slopes on Anderson Ranch Dam was based with some confidence on the results of the slope stability analyses and the earthfill strength data developed by Reclamation's Earth Materials Laboratory. The contractor on Anderson Ranch Dam introduced a number of innovations during construction, including the use of a belt conveyor system for the

transporting the borrow material to the embankment, with facilities for adding moisture to the material moving along the belt conveyor.

After Dr. Terzaghi and others began to develop geotechnical engineering during Period II, and after the First and Second Congress on Large Dams meetings in 1933 and 1936, Reclamation's engineers joined the national and worldwide efforts in advancing the new field as it related to embankment dams. Reclamation continued to develop and make available information on its engineering work. A second edition of *Dams and Control Works* was published in February 1938 [22]. This soft-cover 261-page book, again written by Reclamation engineers, contained three parts: One - Storage Dams; Two - Diversion Dams; and Three - Special Articles. Part 3 still included an article by Engineer F. F. Smith on "Design and Construction of Small Earth Dams." Paragraph 5 of that article contains the statement: "Among Engineers charged with the responsibility for the safety of large earth dams, it is appreciated that the outworn empirical methods have given way to thorough preconstruction investigations, careful theoretical design, and construction on known and definite principles of soil mechanics." [23] A figure in the article on page 254 portrays "Methods of Zoning Earth Dams," and notes that zones 2 and 3 (zone 2 flanks the zone 1 impervious core and zone 3 is located between zone 2 and the rockfill zone on the downstream slope) "are roughly graded from fine material at the inner slopes to coarse at the outer slopes". This grading from finer grained material at the zone 1 core to coarser grained material toward the outer slopes was generally used on Reclamation's embankment dams, and provides the filtering action necessary to prevent soil "internal erosion" (piping). Dr. Terzaghi seems to have started the work to develop rational filter criteria. The results of his work and the research work by George E. Bertram with the assistance of Dr. Terzaghi and Prof. Arthur Casagrande (Honorary Member, ASCE) resulted in a paper by Bertram [24] that is generally given the credit as the first document on filter criteria. The Corps conducted its own research into filters in the early 1940s.

Field and laboratory testing of soil and rock materials continued to be refined in response to the need of designers to better characterize those materials for potential use in embankment dams. As noted above in the discussion of Anderson Ranch Dam, the Earth Materials Laboratory was able to provide the engineering data necessary to optimize the design of the embankment slopes to be constructed.

Reclamation's instrumentation for and monitoring of embankment dams continued to be improved, with the development and installation in 1935 of 13 water level indicators (WLI) at Hyrum Dam and 12 more WLIs at Agency Valley Dam. The water level indicators were a combination manometer and piezometer, but it was not sufficiently accurate. This lead to the development of the hydrostatic pressure indicator (HPI), a modification of the Goldbeck cell, which were installed at Caballo Dam, Alcova Dam, and several other dams in 1938 and 1939. The hydrostatic pressure indicator used a thin gold-plated monel-metal diaphragm, which used air pressure on one side to balance and measure the porewater pressure on the other side of the diaphragm. The HPIs were installed in the embankment as it was constructed, and copper tubing was run in trenches from the instrument to the embankment surface where a recording apparatus

could be attached and operated to measure the porewater pressure. Reclamation developed the more-rugged hydraulic piezometer that could be installed in either the foundation or the embankment; the first 72 hydraulic piezometers were installed at Fresno Dam in 1939. Reclamation also developed the internal vertical movement device, which was first installed at Caballo Dam in 1936. The device was installed as the embankment was constructed and allowed the vertical consolidation behavior of the embankment to be measured at 5- or 10-foot intervals and also measured the settlement of the foundation at the bottom.

During Period III, the equipment available for the construction of embankment dams continued to improve in size, power, speed, and efficiency. The rockfill zones included in these dam embankments could now be constructed because the construction equipment now permitted the handling of larger and larger sizes of rock particles, which were usually obtained from the required excavations for the outlet works and/or spillway. The improved construction equipment and improved techniques for dewatering below the groundwater table allowed the excavation of cutoff trenches through overburden soils to become larger and deeper where necessary.

Period IV (1945-1975)

Reclamation's state-of-the-practice in embankment dam design and construction at the beginning of Period IV had developed to quite a high degree of sophistication. Reclamation's projects and dams were generally written about in engineering and construction publications as indicative of the state of the practice. Reclamation's reputation and those of its engineers continued to grow as more milestone embankment dams were designed and constructed during Period IV. Reclamation's Chief Engineers during Period IV were Walker R. Young, Leslie N. McClellan, Grant Bloodgood, (both McClelland and Bloodgood were also Assistant Commissioners), Bernard P. Bellport, and Harold G. Arthur (both Bellport and Arthur were also titled Director, Office of Design and Construction).

The embankment dams designed and constructed during Period IV generally involved more difficult and complex damsites than had been built on before, and the resulting designs were more complex. After World War II, a new rush of dam construction occurred because of the delays caused by the war. The multi-purpose dam and project came into being at Reclamation, expanding its previous focus on irrigation projects and storage dams. Significant improvements were made to the construction equipment available at the start of Period IV.

Laboratory testing of earthfill materials saw new improvements in the quality and size of the apparatuses and instrumentation available for conducting soil and rock testing, aided especially by the introduction of computers for automated data acquisition during testing. Starting around 1957, Reclamation started to use computers in laboratory testing and in the analysis of slope stability. Larger sizes of testing equipment allowed research and development of data on the effects of larger-size particles on the shear strength of the true matrix of earthfill materials being used in embankment dams. The improved instrumentation used in monitoring the testing allowed them to be run more slowly and allowed for the measurement of porewater pressures generated

during shearing of the saturated specimens. Reclamation's research into filters was conducted by K. P. Karpoff, which lead to *The Use of Laboratory Tests to Develop Design Criteria for Protective Filters* published in 1955 [25].

In October 1961, Waco Dam in Texas, a Corps dam, suffered a slope failure during construction that dropped the crest 18 feet vertically and caused horizontal movements of up to 26 feet downstream. The slope failure was caused by a combination of high porewater pressures in the foundation clay shale generated by the weight of the overlying embankment that were transmitted through a sand layer and the failure of the low shear strength clay-shale foundation. Research on testing the Waco Dam foundation clay-shale material and improvements in slope stability analyses resulted from that event (this became important to Reclamation at the end of Period IV and the beginning of Period V).

Sheffield Dam near Santa Barbara, California had failed in 1925 due to earthquake-induced soil liquefaction in the dam's foundation. Reclamation became more concerned about the seismic stability of its embankment dams in the late 1940s and early 1950s, and a technical memorandum entitled *Seismic Stability of Earth Dams* [26] by Civil Engineer Elbert E. Esmiol (Life Member, ASCE and USCOLD/USSD) was published in April 1951. Several large earthquakes occurred during Period IV, which lead to the development of new soil tests and methods of analysis, trying to model the loading of and the response by the various soils that occurred during those earthquakes. The powerful earthquakes that occurred at Nigata, Japan, and in Alaska in 1964 caused geotechnical engineers to begin research on how to model the soil behavior called "liquefaction" that was exhibited by sandy soils during those events. The near-breaching of Lower Van Norman (San Fernando) Dam during the 1971 earthquake that hit the Los Angeles area caused a renewed burst of research into soil liquefaction, field and laboratory testing, and modeling of the deformations that occurred in the upstream portion of the Lower Van Norman Dam, a hydraulic-fill embankment. Reclamation's Soils Engineering Branch participated in the evolution of field testing and laboratory testing of liquefaction-susceptible sandy soils after the near earthquake-induced upstream slope failure of Lower Van Norman Dam. Starting around 1962, computers had begun to be used to analyze soil stresses with the newly-developed finite-element method of analysis. This analysis method was subsequently upgraded to allow the Lower Van Norman Dam embankment and foundation to be modeled, and to estimate the deformations produced by the earthquake shaking for comparison with the actual deformations.

Many embankment dams were designed and constructed by Reclamation during Period IV. These included: Davis, Granby, Martinez, Box Butte, Scofield, Shadow Mountain, Cascade, Dixon Canyon, Spring Canyon, Soldier Canyon, Long Lake, Dry Falls, O'Sullivan, Jackson Gulch, Enders, Medicine Creek, Heart Butte, Bonny, Cedar Bluff, Shadehill, Dickinson, Trenton, Kirwin, Webster, Cachuma, Carter Lake, Glen Anne, Lauro, Rattlesnake, Tiber, Jamestown, Palisades, Sly Park, Wanship, Lovewell, Casitas, Vega, Trinity, Navajo, Fontenelle, Merritt, San Luis, Soldier Creek, Pueblo, and Teton Dams. These Period IV embankment dams generally had upstream slopes that ranged from 2.5:1 to 3.5:1, with flatter slopes ranging from 4:1 to 20:1 at the toe where excess material could be wasted. The steep 2.5:1 upstream slopes were used only

where an upstream rockfill zone created the necessary strength and stability. The downstream slopes ranged from 2:1 to 2.5:1, similarly with flatter slopes ranging from 3.5:1 to 20:1 at the toe. These dams were built on a variety of foundations; all of them were either founded on bedrock or they included a cutoff trench excavated down through the overburden soils to bedrock, and quite a few of them included concrete cutoff walls in the bottom of the cutoff trench. The cutoff trenches remained near the upstream center of the dam. The rockfill material from required excavations was generally placed and compacted in the outer slopes of the embankment.

Granby Dam, completed in 1948 with a maximum height of 235 feet above the streambed, encountered several construction problems that were successfully dealt with. A significant change in the borrow source for the embankment was accomplished with little adverse effect on the schedule. An attempt was made to use the surface mapping of the damsite's geology instead of the usual amount of investigative drilling; however, the use of this approach (used elsewhere) proved to be inappropriate due to the complex geology of the damsite. The construction experience on Granby Dam was discussed in F. C. Walker's publication: "It was necessary to perform additional grouting after the structure was placed in operation. However, this grouting was accomplished so economically that portions of other dams have since been left ungrouted until actual performance indicates a need for such treatment." [27] This insight into Reclamation's foundation grouting design philosophy by the then Head of the Earth Dams Section becomes more meaningful when Fontenelle and Teton Dams are discussed.

Davis Dam, which spans the Colorado River, was completed in 1950 with a maximum height of 138 feet above streambed. This dam represented an important advancement because of the diversion scheme for bypassing the large flow of the river around the damsite. That diversion was accomplished by excavating an open channel through the left abutment that was later closed by the construction of a concrete dam, which contained the spillway and the hydroelectric powerplant penstocks.

Construction of Enders, Medicine Creek, and Heart Butte Dams and several other embankment dams were all begun around 1946 and 1947 in the Great Plains area where the foundations generally consisted of relatively weak Cretaceous and Tertiary formations of sand, silt, and/or clay. These formations tend to be fairly permeable if sandy or structurally weak if clayey. The valley floors are generally broad and are covered with moderately deep alluvium. The available borrow materials usually ranged from sandy silts to silty clays, with both gravel and rock (suitable for use as riprap) scarce to nonexistent. This damsite also had stream flows that were highly variable, with large floods possible. It proved to be cheaper to increase the size of the reservoir to increase flood-storage capacity rather than build a larger spillway.

Cachuma (Bradbury) Dam, completed in 1953 with a maximum height of 206 feet above the streambed, was constructed in a highly seismic area close to where Sheffield Dam had failed during an earthquake in 1925. The design of the embankment dam was therefore more conservative than would have otherwise been necessary. A large amount of siltstone and shale rockfill was produced by the spillway excavation, and this otherwise unsuitable material was used

by enclosing it entirely within the downstream sand and gravel zone. In one of the first applications, a concrete "grout cap" was constructed at the bedrock surface in the center-bottom of the cutoff trench at Cachuma Dam to provide firm support for the curtain grouting of the foundation beneath the dam.

Tiber Dam, completed in 1956 with a maximum height of 196 feet above the streambed, was built on a shale foundation that contained numerous seams of low shear strength bentonite clay. Hence, the foundation shear strength was uncertain. The earthfill materials available for use as the embankment's central core varied widely in characteristics and shear strength, which was expected to be low. The embankment cross section therefore reflected these concerns with a waste material disposal zone between the upstream cofferdam and the upstream slope, and with downstream slopes ranging from 2.25:1 near the crest to 5.5:1 toward the toe. The embankment also included zones flanking both sides of the core that transition between the finer-grained clay, silt, sand, and gravel core founded on bedrock and the coarser outer shells that consisted of sand, gravel, and cobbles.

Palisades Dam, completed in 1957 with a maximum height of 260 feet above the streambed, was one of the largest embankment dams yet built by Reclamation. The embankment volume of over 13,500,000 yd^3 caused the design to use nearby borrow materials that might otherwise have been rejected. The borrow soils available were pervious sand and gravel alluvium on the valley floor and impervious soils along the abutments, which had moisture contents either too high or too low with respect to optimum moisture for compaction. There was also some concern about potentially high construction porewater pressures created by the weight of the fill. The design was adjusted to place the better but wetter borrow soils in the lower and central parts of the embankment and the drier but poorer borrow soils in the upper and outer parts of the embankment, while still maintaining adequate slope stability.

Sly Park Dam, completed in 1954 with a maximum height of 175 feet above the streambed, was one of the first and few rockfill embankment dam designs built by Reclamation. The upstream rockfill slope was 2.5:1 and the downstream rockfill slope was 2:1. Because of the size of the rockfill particles, the rockfill material could not be tested in the laboratory. The design therefore had to assume that the shear strength should reflect the natural slopes of the loose rock in the vicinity (the angle of repose). Again, the central core of compacted silt, sand, and gravel was flanked by transition zones, consisting of quarry fines in this case. Because of the difference between the properties of the compacted central core and the rockfill shells, differential consolidation between these zones later caused longitudinal cracks along the crest.

Although vibratory rollers had been developed for compacting cohesionless soils for roads in Europe in the 1930s, they were first used to compact rockfill dam materials at Quoich Dam in Scotland around 1958. In the United States, the use of vibratory rollers for compaction of rockfill materials was first attempted by the Corps at the 445-foot-high Cougar Dam in Oregon, built between 1959 and 1964. Reclamation first used smooth steel-drum vibratory rollers to compact a sand and gravel zone at Navajo Dam in 1959. [28]

Trinity Dam, completed in 1962 with a maximum height of 465 feet above the streambed, is the highest embankment dam ever designed and constructed by Reclamation, and its volume of 29,400,000 yd^3 made it the largest yet built. Almost all of the overburden material was excavated such that the embankment rested almost entirely on bedrock. The embankment contained four zones, grading from the central core to outer toe zones of rockfill. The upstream slope ranged from 2.5:1 in the upper slope to 4:1 in the lower rockfill toe zone. The downstream slope ranged from 2:1 near the crest to 3:1 in the lower rockfill toe zone. The upstream and downstream rockfill toe zones were added to improve stability; the rockfill was placed in 3-foot-thick layers (without compaction). A belt conveyor system over 10,000 feet long, that dropped 1,000 feet in elevation and handled 1,850 yd^3/hr, moved a total of about 10,000,000 yd^3 of earthfill material from the borrow area to the damsite.

Navajo Dam, completed in 1963 with a maximum height of 388 feet above streambed, had a miscellaneous earthfill zone downstream of the central core that was completely enclosed within a zone of "selected sand, gravel, cobbles, and boulders." That selected sand, gravel, cobbles, and boulders zone formed an inclined transition/drain zone between the core and the miscellaneous earthfill and formed a blanket/drain zone against the downstream bedrock foundation.

Fontenelle Dam, completed in 1964 with a maximum height of 128 feet above streambed, included: irrigation canal outlet works in both abutments, a river outlet works near the middle of the dam capable of passing 18,700 ft^3/s, a hydroelectric powerplant, and a right abutment overflow spillway of 20,000 ft^3/s capacity at full pool. The river outlet works was large because it was less costly than increasing the size of the spillway. The embankment cross-section is shown in **Figure 11** below. The embankment zoning included: the zone 1 core, the zone 2

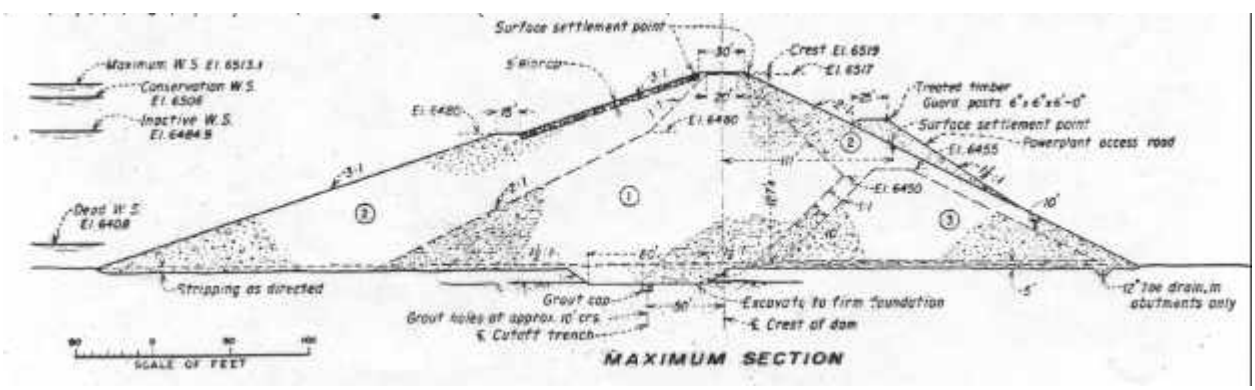

Figure 11 - Fontenelle Dam Section

chimney and blanket drain of selected (pit run alluvium) sand, gravel, and cobbles, and a zone 3 miscellaneous fill that was completely enclosed within the Zone 2. The surface of the bedrock foundation was far more broken than had been anticipated, so the cutoff trench was deepened by 6 feet. The foundation and abutments were grouted by a single-row grout curtain installed through a grout cap. Grout takes in the upper 65 feet of the foundation were very large and a

second line of grout holes was placed in the vicinity of the river outlet works and in the right abutment to perform additional grouting. The grouting program included a total of 45,900 linear feet of drill hole and 143,000 ft^3 of cement grout pumped into the foundation, for an average grout take of 3.1 ft^3 per foot of hole. Reservoir filling was to be very slow so that if any seepage leaks occurred, <u>they could be plugged before permanent operations commenced</u> (remember the previous reservoir filling and additional grouting experience on Granby Dam.) There was no surface treatment of the foundation rock beneath the zone 1 core, such as slush (lean cement) grouting of surface cracks, and smoothing of the foundation with dental concrete.

First filling of the 345,000 acre-foot reservoir commenced in April 1964. During the summer of 1964, after the reservoir had risen to a depth of about 49 feet, seepage appeared in the floor of an exhausted borrow area 2,000 feet downstream of the dam and stabilized at a flow of 6 ft^3/s. The reservoir continued to fill through the spring runoff from the heavy snowpack winter of 1964-1965 (which produced a peak reservoir inflow of 17,560 ft^3/s) until it reached a depth of about 85 feet in early June 1965. Seepage then began to discharge from a rock cut in the spillway discharge channel and from a cliff face about 0.6-mile downstream on the left abutment. The seepage flowing from the downstream borrow area also appeared to have increased. The reservoir began to spill on June 15th and the rate of total seepage increased to about 70 ft^3/s. A small slough occurred at the edge of the embankment on the left side of the spillway chute at about the mid-height of the dam on June 29th, with about 1 ft^3/s issuing from a crack in the rock beneath the chute. On the morning of September 3rd, a wet spot was observed on the downstream slope of the dam at about mid-height near the right abutment about 100 feet to the right of the slough that occurred in June. By mid-afternoon, seepage water started flowing from the wet spot area, causing erosion and sloughing of the dam embankment material. The flow that evening was estimated at about 5 ft^3/s. Local officials were then alerted to stand by, ready to evacuate downstream residents. The next morning (September 4th), the seepage flows had increased to about 21 ft^3/s and an estimated 10,500 yd^3 of material had been eroded from the downstream slope (see **Figure 12** on next page). Rockfill was dumped into the hole on the downstream slope, trying to stop the erosion, and the seepage flows appeared to stabilize. On the morning of September 5th, it was decided to fully open the outlet works, and by the morning of the 6th the reservoir level had dropped 8 feet from the initial level. That afternoon, an area on the dam crest about 20 feet in diameter near the upstream edge collapsed (see **Figure 13** on page after next page) and dropped about 30 feet, exposing bedrock on the abutment side of the cavity. The reservoir continued to drop about 4 feet per day until the pool was low enough to halt the seepage.

There were several causes for the near-breaching (and near-failure) of Fontenelle Dam, which was barely avoided because of the large outlet works capacity. According to Chief Engineer Bellport's "appraisal of the accident" included in his paper *Bureau of Reclamation Experience in Stabilizing Embankment of Fontenelle Earth Dam* [29] presented at the 1967 ICOLD Conference

Figure 12 - Fontenelle Dam - Large Sinkhole on Downstream Slope

in Istanbul, Turkey, "It is apparent that the weak spot was in the abutment and not the embankment. Many dams have been placed on similar foundations. ... With steep abutments, it is difficult to obtain adequate shallow grouting because of the low pressures that must be used to prevent movement in the foundation." [30] The single row grout curtain was judged to have been inadequate, given the nature of the sedimentary shale and sandstone bedrock jointing in the abutments. The problem was (supposedly) fixed by a grouting program consisting of eight lines of grout holes in the steep right abutment; a total of 80,000 feet of hole was drilled and an additional 200,000 ft^3 of grout were pumped into the abutments during August-December 1966. Bellport commented in the paper that "In the 20-year span from 1940 to 1960, increasing boldness in reducing the number of lines and amount of grout seemed to be proving a philosophy that grouting was mostly superfluous. At the Bureau of Reclamation too, in situations where deficiencies could be readily remedied, the process of "try and see" was being used with increasing success until the situation at Fontenelle Dam was encountered." [31] Further, "This difficulty occurred on first filling of the reservoir which was unusually rapid due to extremely large inflows and the fact that the outlet works was not being used so that some repair work

Figure 13 - Fontenelle Dam - Crest Sinkhole

could be performed. This experience illustrates the need for slow, controlled filling of reservoirs where unfavorable foundation conditions are known to exist." [32] Within Reclamation, it appears that information on the near failure of Fontenelle Dam may not have been widely distributed, but other organizations, such as the Corps, reportedly changed some of their embankment dam design and construction practices after reviewing this incident. Fontenelle Dam will be discussed further under Period V.

Merritt Dam, completed in 1964 with a maximum height of 120 feet above the original ground surface, was the first embankment dam that used "soil cement" instead of rock riprap to protect the upstream slope. Merritt Dam is located on the Snake River in north-central Nebraska where the usual rock riprap material was not economically available. Reclamation had developed and successfully used soil cement on a test section constructed in 1951 at Bonny Reservoir in eastern Colorado. Since its first success at Merritt Dam, soil cement slope protection has been used on twelve more embankment dams by Reclamation and on countless other structures.

San Luis Dam, completed in 1967 with a maximum height of 244 feet above the original ground

surface and a volume of over 77,000,000 yd^3, is the largest embankment dam by volume ever designed and constructed by Reclamation. The embankment included a central impervious core with a volume of about 42,000,000 yd^3. The borrow material was excavated using a Bucyrus-Erie wheel excavator with a 30-foot-diameter digging wheel equipped with ten 2½ yd^3 buckets. This machine had a capacity of about 4,000 yd^3/hr and loaded a 100-ton Euclid bottom-dump truck every 45 seconds. In September 1981, a rapid-drawdown of the reservoir lead to a slide in the upstream slope that was caused by a weak clay layer in the foundation. The slide was about 1,300 feet long and involved the reconstruction of the upstream slope and construction of a berm along the toe, with a total volume of about 1.4 million yd^3.

Soldier Creek Dam, completed in 1973 with a maximum height of 251 feet above streambed, was built to enlarge the reservoir originally impounded by the 1913-era Strawberry Dam, which was then breached when the water on both sides equalized. The design and construction of Soldier Creek Dam were similar to Fontenelle Dam. Soldier Creek Dam was one of seven dams (both embankment and concrete dams) selected by the Department of the Interior for a post-Teton 1977 study by W. A. Wahler & Associates to review recently completed Reclamation dams. Soldier Creek Dam will be discussed further in the Period V section.

Pueblo Dam, completed in 1975 with a height of 165 feet above original ground, was a composite dam consisting of a concrete massive-head buttress structure containing the 550-foot- long spillway, flanked by two earthfill embankments. The concrete structure was 1,750 feet long and consisted of 23 buttresses with a maximum height of 176 feet. The two wing embankments wrapped around the ends of the concrete structure and consist of the 3,570-foot-long left embankment and the 4,910-foot-long right embankment. Bedrock at the damsite consisted of flat-lying Cretaceous sediments in alternating units of sandstone, limestone, and shale. The concrete dam section was founded on Dakota sandstone and the embankments rest partly on alluvium in the valley bottom and on Graneros shale on the gently rising abutments. The Dakota sandstone contained a few discontinuous lenses and seams of shale. The Graneros shale contained a number of seams of bentonite clay up to 6 inches thick. When the left embankment had risen to within about 20 feet of the final crest elevation in November 1973, the inclinometer casing located at the downstream toe at station 90+00 indicated a downstream shear deformation through the casing that prevented the lowering of the inclinometer instrument. Additional inclinometer casings were installed along the downstream toe of the left embankment, which finally indicated the deformation had stopped, after reaching a total of about 6 inches of downstream deformation. There were no piezometers installed in the shale or the bentonite clay seams prior to embankment construction that might have indicated the amount of construction-induced porewater pressure in the foundation. Sampling and laboratory testing of the Graneros shale were performed, and finite element analyses were conducted to help judge whether a long-term stability problem was indicated by this foundation deformation. This left embankment deformation in the foundation, which occurred during construction, appears to have been similar to what occurred during construction at Waco Dam in 1961, although not to the same degree. The left and right embankments were both completed and the dam and reservoir were put into service. Pueblo Dam will be discussed further in the Period V section.

Teton Dam was constructed between February 1972 and November 1975, with a maximum height of 305 feet above the streambed. The embankment cross-section was remarkably similar to that of Fontenelle Dam (see **Figure 14** below). The wide zone 1 core consisted of silt, flanked

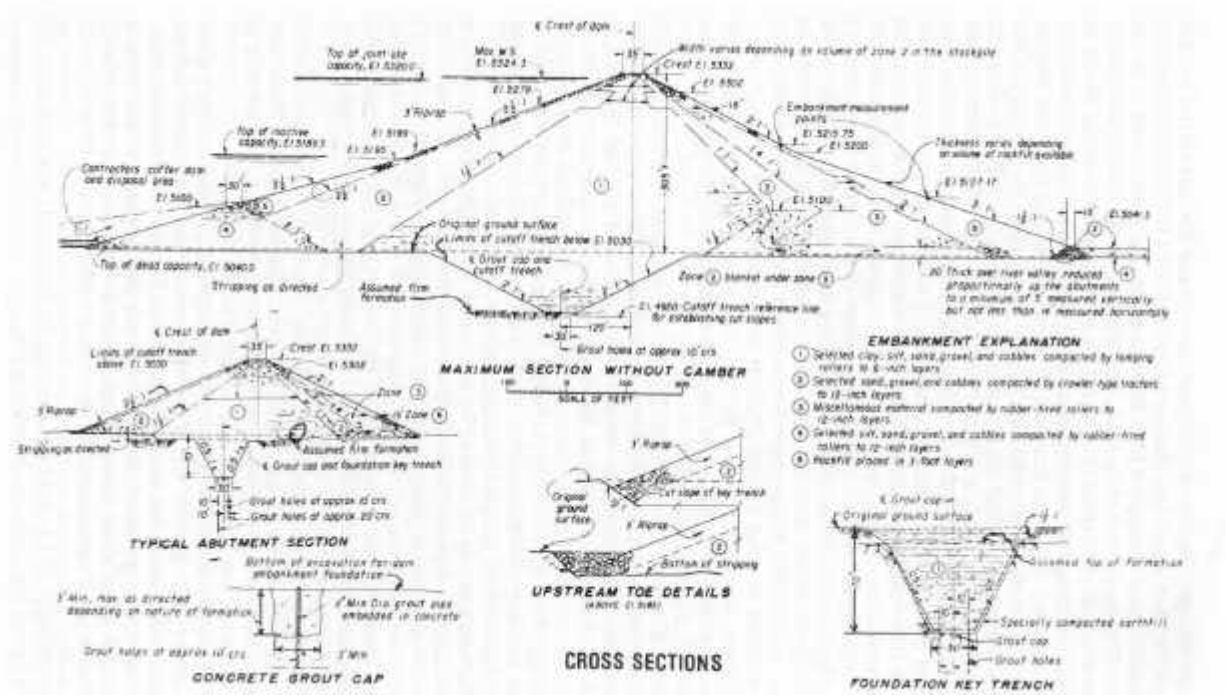

Figure 14 - Teton Dam Sections

upstream and downstream by zone 2, which consisted of (pit-run alluvium) selected sand, gravel, and cobbles. There was also a zone 3 miscellaneous earthfill zone downstream, with zone 2 constructed as a chimney filter/drain and as a 20-foot-thick drainage blanket beneath the zone 3 and up the abutments. The outlet works at Teton Dam consisted of the river outlet works with a capacity of 3,400 ft^3/s and an auxiliary outlet works with a capacity of 850 ft^3/s. The construction schedule required that the river outlet works be operational by May 1, 1976, but the contractor was behind schedule and only the auxiliary outlet works were operational to control reservoir filling.

Foundation grouting at Teton Dam consisted of 3 lines of grout holes up to 310 feet deep. A test-grouting program was conducted in 1969 and was to inject about 260,000 ft^3 of grout into the foundation. The actual test grouting program pumped twice that amount of grout during the pilot grouting program, and just two of the test holes took 16,000 sacks of cement and 18,000 sacks of sand, for an equivalent total of about 34,000 ft^3 of grout. During actual construction, the grout was injected into 118,179 lineal feet of drilled holes and totaled: 496,515 ft^3 of cement, 82,364 ft^3 of sand, 132,000 pounds of bentonite, and 418,000 pounds of calcium chloride. Looking at just the cement and sand grout materials, the above figures equate to about 4.9 ft^3 per foot of drill hole, or an increase of over 50 percent compared to the initial grouting done at

Fontenelle Dam. Beneath the zone 1 core, the rock foundation surface was cleaned using air and water jets and some open joints and cracks in the bottom of the key trenches and the cutoff trench were treated by installing pipes and grouting with a grout slurry, or by filling with specially compacted zone 1 material. Surface grouting stopped at elevation 5205. [33] The instrumentation installed at Teton Dam consisted of surface settlement points and strong motion accelerographs; there were no piezometers installed in the dam embankment or foundation. Reclamation's embankment dam design engineers made only two visits to the damsite during construction; the construction liaison engineer made six visits during construction.

Data on the dam obtained during subsequent investigations were summarized in the paper *Teton Dam: Summary of Technical Investigations* by D. J. Duck, R. W. Kramer, and L. W. Davidson that was presented at the 13th ICOLD Congress in New Delhi, India in 1979 [34]. The zone 2 chimney filter and drainage blanket located downstream from the core was intended to: filter the zone 1, prevent water from attacking the zone 3, reduce seepage pressures, and transmit seepage flows to the downstream toe. The permeability of the zone 2 material was not tested prior to construction. The zone 2 contained 2 to 12 percent silt fines, average 4.5 percent; had been placed at a relative density ranging from 80 to 120 percent, average 94 percent; and had a permeability that ranged from 0.7 to 39.3 x 10^{-6} cm/s, average 9.4 x 10^{-6} cm/s. The zone 1 silt had a mean horizontal permeability of 5 x 10^{-6} cm/s, which was just a bit lower than the average for the zone 2 material [35]. These permeability numbers indicate that the zone 2 filter/drain material was nearly as impervious as the zone 1 core material. According to Peter Aberle, Field Engineer on Teton Dam construction, when it rained during construction, the water would pond on the zone 2 surface [36]. It appears that the as-constructed zone 2 did not have sufficient permeability to function as the intended blanket drain.

First filling of the 288,000 acre-foot reservoir commenced in October 1975 with the reservoir at elevation 5060. The design considerations required that the reservoir not be filled faster than 1-foot per day above elevation 5200. In early March 1976, with the reservoir 135 feet deep at elevation 5170, the filling rate limit in the design considerations was "relaxed" and filling rate of 2 feet per day was "allowed" to accommodate the high reservoir inflows from a large snowmelt runoff. However, they had no other option but to relax the reservoir filling rate limit and accept the 2-foot-per-day rate of rise - the river outlet works weren't yet operational! By early May 1976, the reservoir was 185 feet deep. The decision was "made" (note once again the inoperable river outlet works) around May 13th to fill the reservoir to the spillway crest, which lead to an average filling rate of about 3 feet per day, and a maximum rate of 4.3 feet per day. Teton Dam failed catastrophically on June 5, 1976, when the reservoir had reached the spillway approach channel at elevation 5301.7. The failure of this embankment dam killed 11 people, left 25,000 people homeless, inundated partially or completely an area of about 300 mi^2 that extended 80 miles downstream, and did property damage estimated at about $400 million. This dam failure changed the Bureau of Reclamation in many, very significant ways. The construction of Teton Dam therefore completes Period IV. The failure of Teton Dam will be discussed further in the Period V section.

During Period IV, Reclamation's engineers continued to enjoy national and worldwide acclaim as they helped to advance the new field of geotechnical engineering and its sub-specialty of embankment dams by conducting research and publishing reports and professional society papers. Reclamation continued to develop and make available information on its engineering work. A total of 6,000 copies of the "tentative edition" of Reclamation's *Earth Manual* were printed and distributed in 1951, followed quickly by another 28,000 copies of the "first formal edition". The *Earth Manual* was a huge success worldwide and was in great demand. A First Edition - Revised, Second Printing was printed and distributed in 1968 with 783 pages. The *Earth Manual* combined and revised three earlier manuals: the Earth Materials Laboratory Test Procedures; the Field Manual for Rolled Earth Dams; and the Earth Materials Investigation Manual. The *Earth Manual* was prepared by Reclamation's engineers in the Earth Dams Section, Dams Branch, Division of Design, and in the Soils Engineering Branch, Division of Research, with editing and coordination performed by John (Jack) W. Hilf of the Earth Dams Section. Reclamation's *Design of Small Dams* was published and distributed in 1960, with a Second Edition released in 1973.

Reclamation's instrumentation for and monitoring of embankment dams continued to be improved during Period IV. During the 1950s, several modifications were made to the piezometers used on Reclamation's embankment dams. The tubing used between the hydraulic piezometer tip and the embankment surface was updated to polyethylene tubing. In the 1960s, the tubing was updated again to polypropylene. Reclamation researched and developed the use of carborundum disks in the hydraulic piezometer tips in the 1950s for improved measurement of porewater pressures. In 1959, the use of ceramic filter disks in the piezometer tips was first attempted by Reclamation at Steinaker, Sherman, and Merritt Dams. The first strong-motion earthquake instrument was installed at Hoover Dam in 1937, and Cachuma (Bradbury) Dam was the first embankment dam to have one installed in 1954. There are now over 20 embankment dams instrumented with such devices. As noted earlier, Reclamation seems to have cut back on the amount of instrumentation installed in its dams during Period IV.

During Period IV, the variety of equipment available for the construction of embankment dams continued to improve in size, power, speed, and efficiency. As already mentioned, the wheel excavator used at San Luis Dam produced 4,000 yd^3 per hour, and the earthfill haul trucks used there were 100-ton capacity bottom-dump wagons. The versatile front-end wheel loader with a bucket of up to 12 yd^3 capacity was added to the construction equipment available. Earthfill compaction rollers and scrapers became self-propelled instead of having to be towed behind a Caterpillar bulldozer or tractor. After its initial use at Cougar Dam, the vibratory roller, both the smooth drum and later the tamping pad-foot varieties, became available for improved compaction of earthfill and rockfill materials.

Period V (1976-2002)

At the start of Period V, the failure of Teton Dam on June 5, 1976, began a chain of events during which Reclamation's design and construction organizations changed dramatically. As already mentioned, the first filling of the reservoir was very rapid, due to the earlier-than-usual high

inflows from a heavy snowpack in the mountains upstream. The reservoir inflow peaked at around 4,000 ft^3/s in mid-May. It should be noted again that Teton Dam's main river outlet works in the left abutment, with a full-pool capacity of 3,400 ft^3/s, was not yet operational because the regulating gate had not yet been received from the manufacturer. Only the auxiliary outlet works in the right abutment, with a capacity of only 850 ft^3/s, could be used to control the rate of reservoir filling, or to lower the reservoir water surface in the event of a Fontenelle Dam type of emergency drawdown situation. Hence, even if the main river outlet works had been operational, the releases from the combined outlet works would have been about equal to the inflows and would not have been able to drop the reservoir pool as had been the case at Fontenelle Dam.

On June 3rd, with the reservoir at about elevation 5300, two small seeps flowing about 60 and 40 gal/min were found 1,300 and 1,500 feet, respectively, downstream of the dam at the base of the right abutment. On June 4th, a small seep was found flowing about 20 gal/min at the base of the right abutment about 150 to 200 feet downstream from the toe of the embankment. At about 7:00 a.m. on June 5th, a survey party observed a leak coming from the right abutment at the top of a berm at elevation 5045. It was immediately reported to one of the field engineers who drove to the dam and at 8:15am, he estimated the leak to be flowing 20 to 30 ft^3/s. At about 9:10 am, a slightly muddy leak was observed exiting from the right abutment at elevation 5200, flowing

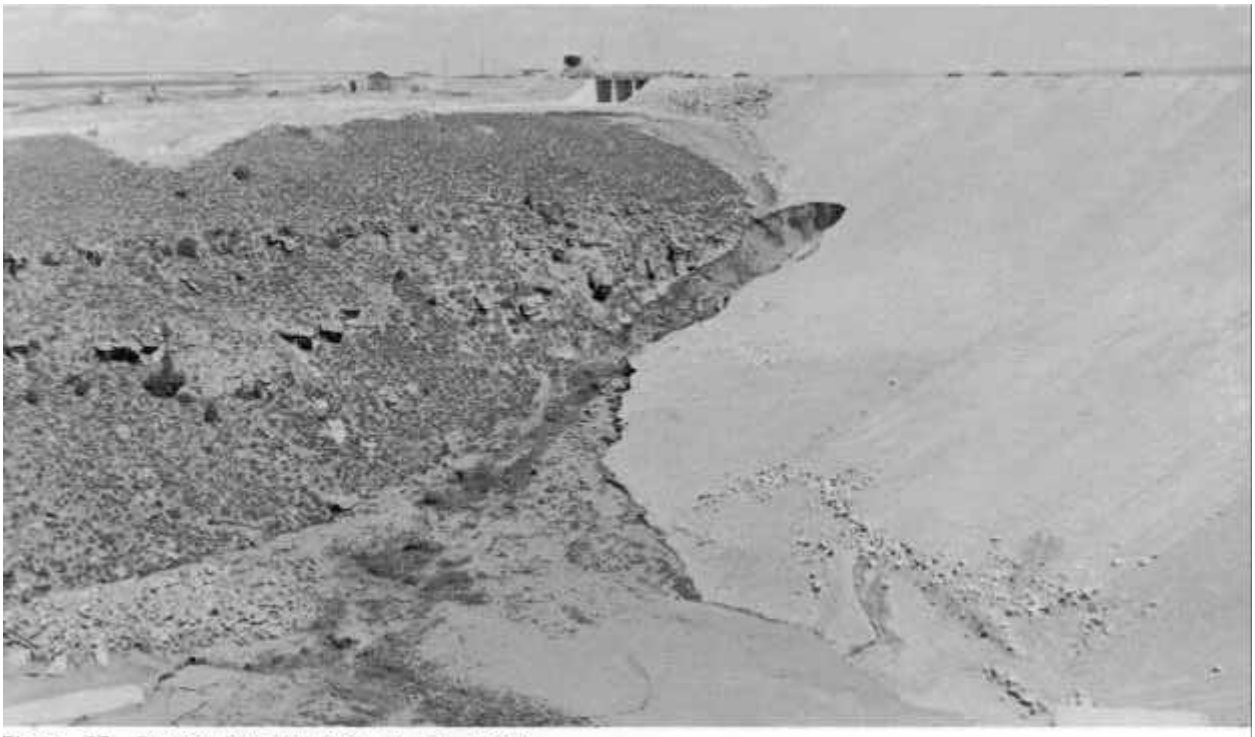

Figure 23.—Dozers lost in leak at El. 5200.

Figure 15 - Teton Dam - Downstream Sinkhole at About 11:20 a.m.

about 2 ft^3/s. The lower leak at elevation 5045 was estimated to be flowing 40 to 50 ft^3/s at about 9:30 a.m. Between 10:00 and 10:30 a.m., a wet spot was observed on the downstream slope of the dam at elevation 5200 and about 15 to 20 feet from the right abutment. The wet spot quickly increased to a flow of 10 to 15 ft^3/s and was eroding the material on the downstream slope. At about 10:30 a.m., a loud sound (roar) was heard, followed by the sound of rapidly running water. At about 11:00 am, a whirlpool formed in the reservoir about 150 feet from the right abutment and its diameter rapidly began to expand. By about 11:20 a.m., attempts to bulldoze rockfill into the opening (as had been done at Fontenelle Dam) proved futile (see **Figure 15** on previous page).

Figure 27.—Dam crest breaching 11:55 a.m., June 5, 1976.

Figure 16 - Teton Dam - Crest Collapsed at 11:55 a.m.

A sinkhole developed on the downstream slope shortly before the embankment crest collapsed at 11:55 a.m. (see **Figure 16** above), and the dam was breached two minutes later at 11:57 a.m. (see **Figure 17** on next page). This sequence of observed new seepage, wet spots, erosion, sinkhole, whirlpool, crest collapse, and embankment breaching took only five hours from start to finish and the complete release of the reservoir followed. By 5:00 to 6:00 p.m. that same day, the reservoir had completely emptied.

On June 8, 1976, just three days after the failure of Teton Dam, the Under Secretary of the Interior, D. Kent Frizzell, established the Department of the Interior Teton Dam Failure Review Group (IRG) that was formed to examine the causes of the dam's failure and to make

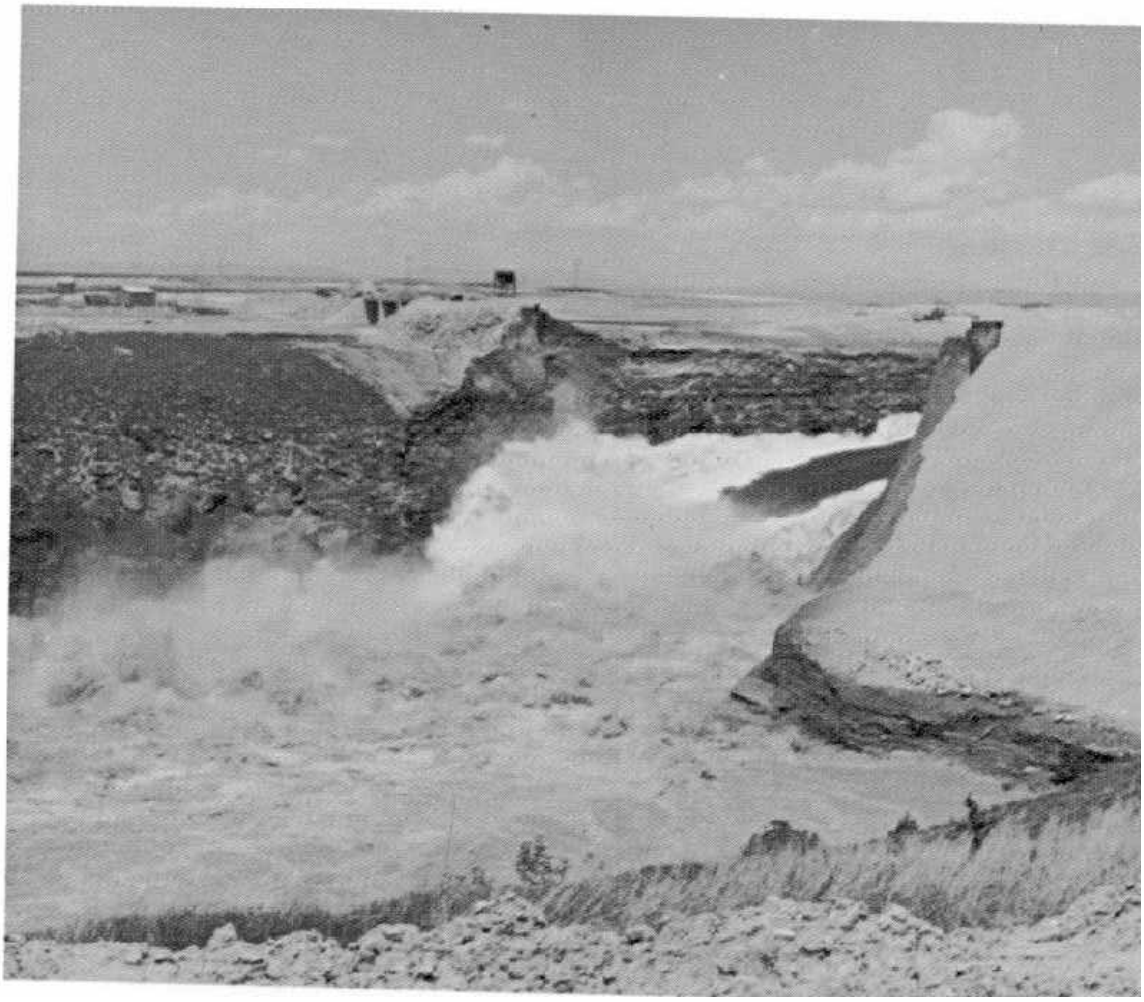

Figure 17 - Teton Dam - Dam Completely Breached

recommendations as appropriate to prevent the recurrence of such failures. The IRG was directed to "review the following aspects of the failure: geologic, engineering, design, construction, hydrologic factors, and all other pertinent background information and testimony." The IRG was composed of representatives from several Federal Government agencies, such as the Soil Conservation Service, the Tennessee Valley Authority, and the U.S. Army Corps of Engineers. The Secretary of the Interior, Thomas S. Kleppe, and the Governor of Idaho, Cecil D. Andrus, empowered another review group of experts not associated with the Federal

Government, who were referred to as the "Independent Panel to Review Cause of Teton Dam Failure" (Independent Panel). The IRG and the Independent Panel operated simultaneously from June to December 1976, with field investigations coordinated and the results shared by the two groups. The Independent Panel's report *Failure of Teton Dam* was published in December 1976

[37]. The IRG's *Failure of Teton Dam - A Report of Findings* was published in April 1977 [33], and its *Failure of Teton Dam, Final Report* was published in January 1980 [38]. The reports/ conclusions of the IRG and the Independent Panel were in general agreement, concluding that the failure of Teton Dam had been caused by:

> 1. Internal erosion (piping) of the core of the dam deep in the right foundation key trench, with the eroded soil particles finding exits through channels in and along the interface of the dam with the highly pervious abutment rock and talus, to points at the right groin of the dam;
>
> 2. Seepage moving through openings that existed in inadequately sealed rock joints, and that may have developed through cracks in the core zone in the key trench;
>
> 3. Once started, piping progressed rapidly through the main body of the dam and quickly lead to complete failure; and
>
> 4. The design of the dam did not adequately take into account the foundation conditions and the characteristics of the soil used for filling the key trench.

Regarding Cause No. 1 above, it should be noted that the apparently impervious zone 2 blanket drain material probably confined the seepage flows and eroded zone 1 core material within the abutment channels, joints, fractures, and cracks all the way to the right groin downstream, and prevented the safe, proper interception and collection of the seepage flows. The nature of the damsite geology, the design of the dam embankment, the treatment(s) of the foundation bedrock surface and open joints (or lack thereof), the characteristics of the embankment materials, the defensive measures taken to control seepage and piping erosion, and the construction practices at Teton Dam were all too similar to those involved on Fontenelle Dam. The IRG and the Independent Panel both recommended that Reclamation should take certain specific measures to prevent the recurrence of another dam failure:

> 1. An independent board of review should be convened for each major dam project to review both design and construction at frequent intervals;
>
> 2. Design decisions should be formally documented;
>
> 3. Design personnel should remain involved with a project during construction, including frequent scheduled site visits; and
>
> 4. Major dams and their foundations should include an instrumentation program to monitor construction and post-construction behavior. Instrumentation data should be promptly interpreted and evaluated.

In a July 20, 1976, letter, the Comptroller General of the United States was asked by U.S. House

of Representatives' Environment, Energy, and Natural Resources Subcommittee to examine the dambuilding procedures and practices used by the Bureau of Reclamation and the Corps of Engineers. The resulting report *Actions Needed to Increase the Safety of Dams Build by the Bureau of Reclamation and the Corps of Engineers* was published on June 3, 1977 [39]. The Comptroller's report discussed several concerns involving the dam designers, recommending that "We recommend that the Secretary of Interior direct the Bureau of Reclamation to establish written procedures to better ensure that design intent is achieved. In so doing the Bureau should: (1) evaluate and implement ways to improve the clarity of instructions, specifications, and drawings; (2) evaluate and implement ways to better ensure that onsite personnel fully understand the intent of the designers, and (3) develop and implement policies and procedures calling for more frequent onsite inspections by designers during construction." [40] The Comptroller's report also noted the comments made in the paper by Chief Engineer Bellport about the lessons learned after the near failure of Fontenelle Dam, and recommended that "Thus, by averting a disaster at Fontenelle, the Bureau had seemingly learned a valuable lesson regarding reservoir filling. Yet, at Teton Dam, over 10 years later, the lesson was not applied." and "We believe that the failure of Teton Dam and the near failure at Fontenelle Dam should clearly illustrate to dambuilders the importance of (1) a slow, controlled filling rate during first filling to closely monitor the behavior of the dam and (2) an operable outlet of sufficient size to release enough water to lower the reservoir level when emergencies arise affecting dam safety." [41]

Reclamation's organization and its state-of-the-practice in embankment dam design and construction at the beginning of Period V, which were thought to have been developed to as high a degree of capability and sophistication as any dam-building organization in the World, were immediately put under the proverbial microscope. In April 1977, President Jimmy Carter ordered all Federal agencies that build, maintain, or operate dams to review their dam safety practices. Reclamation Commissioner R. Keith Higginson named a team to review Reclamation's dam design and construction procedures, and charged the team "to review expeditiously all factors relevant to safety of dams in the Bureau's plan-design-construct-operate process and to develop recommendations which would assure that Bureau procedures follow acceptable standards ..." On March 31, 1977, the Department of the Interior contracted with W. A. Wahler & Associates to conduct a program entitled "An Emergency Study of Seven Completed Bureau of Reclamation Dams." All seven dams were recently completed structures, both earthfill and concrete dams. The seven dams studied by W. A. Wahler & Associates were: Crystal, Mountain Park, Mt. Elbert Forebay, Nambe Falls, Pueblo, Ririe, and Soldier Creek Dams [42]. On November 29, 1977, Commissioner Higginson announced a reorganization plan in which the decentralized field structure was retained, and the Denver Office became Reclamation's center for technical review and support. On November 6, 1979, under Commissioner Higginson, Reclamation changed its name to the "Water and Power Resources Service", but changed it back to the Bureau of Reclamation on May 20, 1981, under Commissioner Robert N. Broadbent.

Reclamation's Chief Engineers (now with different titles, which began as Director, Office of Design and Construction) during Period V were Harold G. Arthur, Robert B. Jansen (title was changed to Assistant Commissioner for Engineering and Research on February 1, 1978), Rodney

J. Vissia, James Cook (acting for 3 or 4 months in 1982), Darrel W. Webber, Felix W. Cook, Sr. (the title was changed once again in October 1994 to Director, Technical Service Center), and Michael J. Roluti.

While Reclamation still had many dams and projects in its "pipeline" awaiting funding and construction at the start of Period V, environmental "clouds" had been gathering on the horizon in both numbers and power and they wanted to put a halt to the continued construction of new dams. The embankment dams that Reclamation designed and constructed during Period V generally involved even more difficult and complex damsites than had been built on before, and the resulting designs were more complex. Part of this increased design complexity was a direct result of the findings and recommendations by the IRG, the Independent Panel, and the Comptroller on the failure of Teton Dam.

The Wahler Reports on seven of Reclamation's recently constructed dams presented some fairly alarming conclusions and recommendations. For example, on Soldier Creek Dam, the Wahler Report concluded that "there may be significant risk of serious distress and/or failure associated with filling the reservoir behind Soldier Creek Dam." And on Pueblo Dam, the Wahler Report concluded that "the reservoir behind Pueblo Dam should not be permitted to rise significantly above its present level until certain supplementary investigations and/or actions have been completed." After the findings of the Wahler Reports were presented to the Department of the Interior (and Reclamation), Reclamation responded by beginning its own reevaluation of these seven dams, which included field and laboratory investigations, new evaluations of the design and construction, etc. With the conclusions and recommendations resulting from the two Teton Dam failure reviews needing to be implemented, Reclamation made dramatic changes in its design and construction organizations.

In 1978, Reclamation instituted its new Safety Evaluation of Existing Dams (SEED) Program under the Division of Dam Safety and reporting directly to the Assistant Commissioner - Engineering and Research (ACER). The SEED Program began a comprehensive review of dam design, construction, and operation records; analysis of material data; field inspections; and study of any apparent deficiencies. The Denver Office's engineering staff was increased to handle the enlarged program. A Technical Review Staff, also reporting directly to ACER, was added to the Denver Office and was tasked with independently reviewing all new dam and major structure designs, modifications to existing dams and major structures, and the SEED Program. Reclamation also hired independent consulting engineers and other professionals to review and approve Reclamation's dam design and construction work.

The work by the Denver Office to respond to the embankment dam concerns raised in the Wahler Reports included field investigations that produced embankment and foundation samples, which needed laboratory testing to develop information on their engineering properties. This additional engineering workload and the laboratory testing workload for projects already planned lead to an increase in the size and capability of the Denver Office Laboratory. Improved electronics and computers were involved with the upgrading of the Laboratory's capability. New testing

equipment was needed in a few cases because of the nature of some of the dam foundation problems encountered and for testing new materials such as synthetic geomembranes and geotextiles. For example, the weak clay seams in the foundation shale at Pueblo Dam required testing for residual shear strength, which Reclamation had never done before.

During Period V, Reclamation continued to design and build some notable embankment dams in the West. These Period V embankment dams included: Mt. Elbert Forebay, Twin Lakes, Palmetto Bend, Funks, Wintering, Red Fleet (Tyzak), Stateline, Choke Canyon, Sugar Pine, Ridgway, Calamus, McPhee, McGee Creek, San Justo, Brantley, Davis Creek, Jordanelle, New Waddell, and Buckhorn Dams. The Period V embankment dams generally had upstream slopes that ranged from 2:1 to 3.5:1 and downstream slopes that ranged from 2:1 to 1.5:1, with the steepest slopes at Jordanelle Dam.

These dams were built on a variety of foundations, but after the foundation problems that in part caused the failure of Teton Dam, the foundation treatments constructed during Period V were more aggressive and more "complete" than those previously constructed. This included design details and features such as: more aggressive cleanup and mapping of foundations, foundation shaping to flatten steep slopes and remove bedrock overhangs, more dental concrete backfill to shape abutments, lean cement (slush) grouting of surface joints, thorough blanket grouting in the upper 20 to 30 feet of the foundation-core contact zone, more lines of curtain grouting, and removal of more poor-quality bedrock in the foundation. The concrete grout cap used at Fontenelle and Teton Dams was also eliminated, grouting from the rock surface, removing any damaged surface rock, or using a reinforced concrete slab so that grout pressure can be applied to near-surface rock. Blanket grouting is then done after the curtain grouting has been completed.

The embankment dam designs changed in several important ways during Period V. The chimney filter/drains placed between the core and the downstream shell material were revised to use processed materials instead to ensure the prevention of internal erosion/piping. A processed transition/filter zone was used between the core backfilling the cutoff trench and the downstream alluvium. Blanket drains were used against the downstream foundation. Processing of borrow soils or the use of imported soil materials to supply the filter gradation(s) necessary was used more aggressively in the chimney filter/drains and the blanket drains. These filters included 1, 2, or even 3 zones of different soil sizes and gradations where necessary to prevent potential internal erosion/piping. These filter/drain systems were interconnected and drained by a perforated toe drain pipe with emphasis on monitoring seepage flows. There was also more emphasis on inspection manholes and monitoring devices in the toe drain system, and more emphasis on the use of relief wells for deeper seepage collection. The design of the embankment constructed adjacent and around concrete structures such as outlet works and spillways changed, eliminating the seepage collars around conduits to facilitate compaction by the tires of heavy equipment rolling next to the conduit instead of regular compaction equipment such as tamping rollers. Processed filters and drains were also placed around the downstream section of the conduits. New synthetic materials such as geomembranes and geotextiles were used in modifications constructed at several embankment dams. Several of the embankment dams noted above,

including San Justo and Jordanelle Dams, were constructed close to major “active” earthquake faults in California and Utah, respectively. Starting with the early work by Esmiol [26], Reclamation has continued to investigate and develop appropriate design requirements for its embankment dams in the earthquake-prone western U.S. that have been used by many others worldwide.

Like other dam-safety programs nationwide, the results of Reclamation’s SEED Program and the reevaluation of the existing dams determined that quite a few existing embankment dams needed to be modified to improve their condition and to ensure their continued safe operation. A partial list of Reclamation’s modified embankment dams includes: Jackson Lake, Helena Valley, Soldiers Meadow (not built by Reclamation), Fontenelle, Navajo, Casitas, Soldier Creek, Pueblo, Lost Creek, Twin Buttes, Twin Lakes, San Justo, Horsetooth (modification under construction), and Pineview (modification being designed) Dams. Reclamation has also been involved with the analysis, design, and construction of modifications to several Bureau of Indian Affairs (BIA) embankment dams, including Black Lake, Pablo, and McDonald Dams on the Flathead Indian Reservation in Montana, and dams belonging to the National Park Service.

Red Fleet (Tyzak) Dam, completed in 1978 with a maximum height of 145 feet above streambed, was one of the first embankment dam designs started by Reclamation after the failure of Teton Dam. Its design cross-section included the new defensive features: a two-stage transition zone and chimney filter/drain, a transition/filter zone between the core backfilling the cutoff trench and the downstream alluvium, and a processed sand and gravel drainage blanket beneath the downstream shell.

Mt. Elbert Forebay Dam, completed in 1980 with a maximum height of 92 feet above the stripped foundation, was built above Twin Lakes as part of a pumped-storage hydroelectric project. The original forebay reservoir was lined with compacted earthfill, but excessive leakage was detected and it could have triggered an ancient landslide, endangering the powerplant at the edge of Twin Lakes Reservoir below. The design was changed to add about 290 acres of 45-mil-thick reinforced chlorinated polyethylene geomembrane liner covered by 18 inches of earthfill.

Pueblo Dam was identified in the Wahler Report as needing certain supplementary investigations and/or actions while restricting its reservoir level. Field investigations were performed and samples of the Graneros shale and bentonite clay seams were obtained for laboratory testing, along with work to resolve several other concerns. Soil testing was performed to determine the residual shear strength of the bentonite clay and the test data were used to re-analyze the stability of the left embankment. The analysis results indicated the downstream slope stability was inadequate and the left embankment had to be modified to increase its stability. An earthfill berm 2,500 feet long and 35 feet high was constructed along the downstream toe of the left embankment in 1980-1981. Subsequent analysis of the concrete buttress dam section and a concern about the low strength shale seams in part of its sandstone foundation resulted in some recent (1999-2000) modifications to improve its resistance to sliding along the shale seams.

Soldier Creek Dam was identified in the Wahler Report as having certain deficiencies that individually or in combination could jeopardize the safety of the dam. Field and laboratory investigations were conducted and Soldier Creek Dam was re-analyzed by Reclamation. The results confirmed that several concerns raised by the Wahler Report were sufficiently serious that modification of the dam embankment was justified. A lack of instrumentation made it difficult to evaluate the performance of the dam embankment, which lead to the installation of over 25 piezometers in the embankment and foundation. The foundation bedrock surface preparation and the lack of proper treatment with lean cement (slush) grout placed in surface cracks, shaping, and dental concrete were of concern. The single-row grout curtain also caused concern. The nature of the zone 1 core material and the fact that it was placed directly against the untreated foundation bedrock caused concern. The permeability of the unprocessed zone 3 chimney filter/drain and blanket drain material caused concern, as did the fact that the chimney filter/drain and the toe drains did not extend all the way up to the full-reservoir water surface. Embankment and foundation drainage modifications were constructed in 1983-1984 to address these problems [43].

Fontenelle Dam continued to have seepage and internal erosion/piping problems after is was supposedly fixed by the additional abutment grouting performed in 1966. Instrumentation monitoring data in 1983 indicated that a potential dam safety problem was developing, and the decision was made to modify the dam by installing a continuous concrete diaphragm wall through the dam and into the foundation. There were several aspects of the existing Fontenelle Dam embankment's design that were judged to have been partly responsible for the failure of Teton Dam, such as vertical to overhanging abutment cliffs, extensive joints and cracks in the abutments, no processed material placed as a chimney to filter the erodible silty zone 1 core as protection against internal erosion/piping, and silty core material placed directly against open, unsealed bedrock joints, cracks, and crevices. Only one solution was judged to be capable of alleviating all of these potential problems, and construction of a concrete diaphragm wall from the crest of the dam down through the embankment and the upper highly-fractured bedrock was selected as the appropriate modification (see **Figure 18** on next page). The concrete diaphragm wall had to avoid damaging the river outlet works near the middle of the embankment and the spillway on the right abutment. The concrete diaphragm wall modification was constructed between 1987 and 1989. **Figures 19 and 20** (on two pages after next page) show the rockmilling equipment used to excavate embankment and rock for the diaphragm wall at Fontenelle Dam.

Black Lake, Pablo, and McDonald Dams are BIA dams on the Flathead Indian Reservation in Montana; Reclamation had designed and constructed Pablo and McDonald Dams between 1905 and 1920. At BIA's request, Reclamation investigated and prepared SEED reports on these three dams, along with the other 14 dams on the Reservation. Under a contract with the BIA, the Confederated Salish and Kootenai Tribes entered into an agreement with the TSC for Reclamation to perform field investigations, laboratory testing, and engineering evaluations to determine the adequacy and safety of the dams on the Reservation. Starting with the dam of

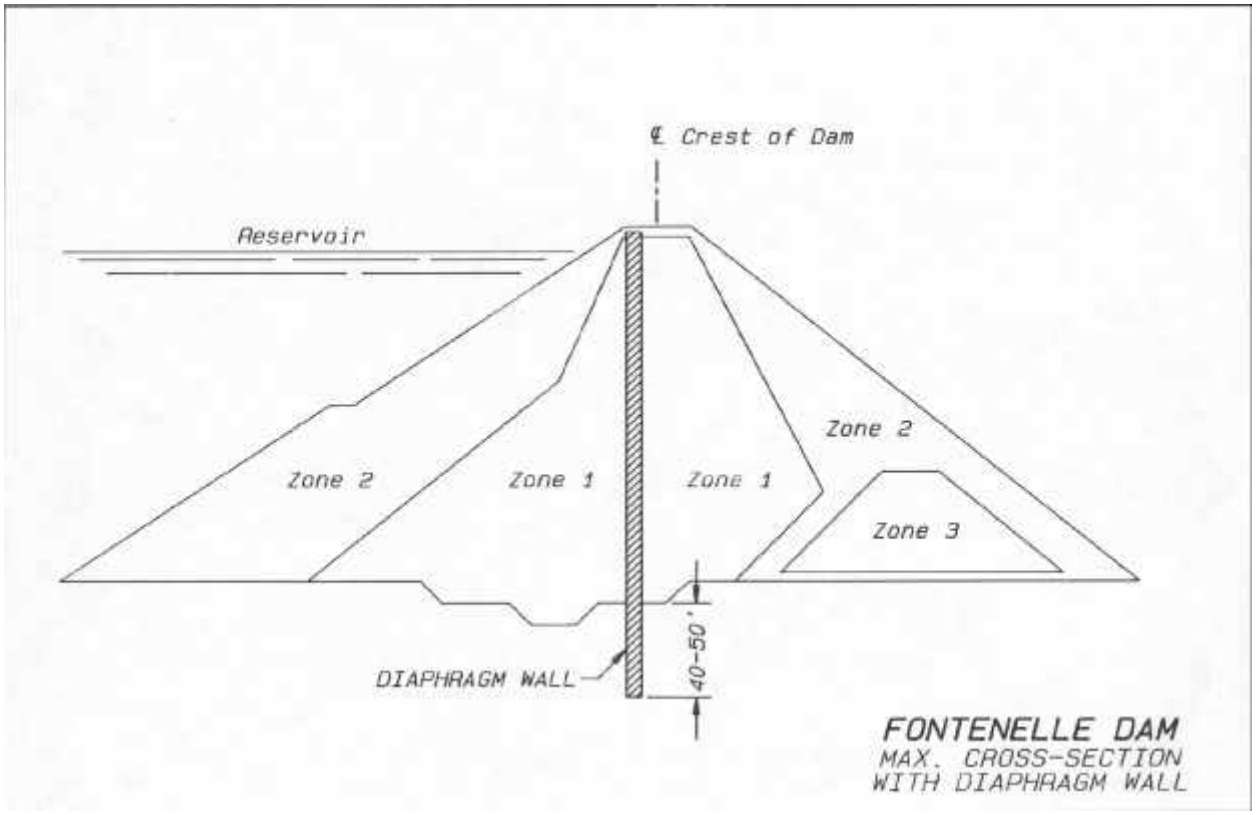

Figure 18 - Fontenelle Dam - Section of Embankment with Diaphragm Wall

greatest initial concern, the investigation and analysis of Black Lake Dam indicated it needed to be modified to prevent a piping/erosion failure. The original Black Lake Dam had failed by internal erosion/piping in 1967, and the replacement embankment dam was judged to have several serious deficiencies that could result in another piping/erosion failure. Black Lake Dam was modified in 1992 by the construction of a geomembrane liner installed along the upstream right abutment, across the upstream slope of the embankment, and as a liner beneath part of the reservoir upstream of the dam. A downstream drainage berm is scheduled to be constructed in the near future and will hopefully remediate the current situation.

Pablo Dam was investigated and analyzed next, and it was determined that the upper portion of the embankment was susceptible to seepage, internal erosion/piping, and potential failure. The upper portion of the dam was more pervious because two embankment raises had been constructed and had used more pervious earthfill material than the original embankment. A geomembrane liner was constructed in 1993-1994, covering the upper embankment to control/prevent the seepage that had been percolating through it.

McDonald Dam was the third embankment dam investigated and analyzed. It was located about ½-mile upstream of the Mission fault, which had experienced a major earthquake about 7,700 years ago, and which was judged capable of producing a magnitude 7½ earthquake at any

Figure 19 - Fontenelle Dam - Diaphragm Wall Construction

time. The dam embankment had been constructed by Project Manager/Engineer Frank Crowe (Honorary Member, ASCE) using dumped and sluiced earthfill, with a puddled core created by sluicing the dumped earthfill (see **Figure 21** on page after next page). The embankment and an outwash foundation beneath part of the dam were judged susceptible to liquefaction and excessive deformation. Various alternatives were developed and evaluated, with the final decision reached to completely replace the existing dam embankment, spillway, and outlet works. These modifications were designed by Reclamation who also provided the construction management services. It should be noted that the Construction Engineer for McDonald Dam Modification was on the Design Team. The new McDonald Dam embankment was a completely different embankment design. The new embankment cross-section included: a textured geomembrane covered by earthfill and riprap on the upstream slope, an impervious earthfill zone behind the geomembrane, followed by an inclined processed chimney filter/drain, all of which rest against a large miscellaneous earthfill zone that sits on top of a blanket drain consisting of processed drainage material sandwiched between two layers of the processed filter material. The instrumentation consisted of piezometers in the embankment and foundation, embankment measurement points, and weirs to monitor seepage flows. These McDonald Dam modifications were constructed in 1994-1995 and 1999-2000 (see **Figure 22** also on page after next), after which its behavior during resumed filling of the reservoir in 2000 and beyond went very well [44].

Figure 20 - Fontenelle Dam - Diaphragm Wall - Hydromill Rock Excavator

Figure 21 - McDonald Dam - Original Dam in 1920

Figure 22 - McDonald Dam - New Dam in 2000

At the beginning of Period V, the failure of Teton Dam and the results of the IRG, Independent Panel, and Comptroller reviews resulted in many organizational changes as already discussed. Several of Reclamation's embankment dam design engineers retired, leaving a small cadre of experienced engineers to work with the new staff of engineers then being hired to work on Reclamation's new dam safety program and on the embankment dam design work already in the "pipeline." That work has been going on for over 20 years now and is expected to continue for some time. Reclamation's current dam safety program includes conducting in-depth reviews, referred to as Comprehensive Facility Reviews (CFR), which are performed mostly by in-house senior engineers every six years. The CFRs include an examination of the dam and evaluations of: the dam's design, analysis, and construction; its structural behavior; its seismic and hydrologic hazards; its potential failure modes; its failure consequences; a risk analysis; and its performance parameters. Reclamation has continued to develop, revise, and make available information on its engineering work. The *Earth Manual* is now in its third edition, with *Part 2* published in 1990 and *Part 1* published in 1998 [1]. *Part 1* of the *Earth Manual* (now containing 1,270 pages) includes updated information on properties of soils, field and laboratory investigations and test procedures, construction quality control testing of earthfill materials used as foundations and for dams, canals, and other types of structures built by Reclamation. *Part 2* (now containing 329 pages) includes updated information on properties of soils, field investigations, and control of earth construction. Reclamation's *Design of Small Dams* was revised and published as a "revised reprint" in 1977 and was revised again and published as the Third Edition in 1987 [2]. In the 1980s, Reclamation developed its Design Standards, with Design Standards No. 13 - Embankment Dams [6] covering all of the embankment dam design issues and concerns; they are all <u>continually</u> updated. Reclamation has continued to make its technical publications available to the public. Reclamation has recently embarked on a new program, generally referred to as risk-based analysis of existing structures, to help with its decision-making process.

Reclamation's instrumentation for and monitoring of embankment dams continued to be improved during Period V. Since their first installation at Fresno Dam in 1939, almost 2,800 hydraulic twin-tube piezometers have been installed at Reclamation's embankment dams. Pneumatic piezometers have more recently been used to measure porewater pressures and vibrating-wire piezometers are now the piezometer of choice installed at Reclamation's embankment dams. In addition to piezometers, other instrumentation often installed at Reclamation's new and modified embankment dams includes: observation wells, seepage weirs, embankment measurement points, strong-motion accelerographs (in earthquake-prone areas), and inclinometer casings with inclinometers to monitor known slide areas. One important aspect of current instrumentation is the use of automated monitoring systems at Reclamation's dams, allowing timely monitoring of embankment dams in remote locations where winter access can be a problem. Such automated monitoring systems also allow the data to be used by early warning systems. The monitoring data are collected by the TSC's Structural Behavior and Instrumentation Group who automatically interprets and evaluates the data in a timely manner, and alerts the appropriate design groups if any of the instrumentation data cause concern. Reclamation's *Embankment Dam Instrumentation Manual* was published in 1987 [45].

During Period V, the variety of equipment available for the construction of embankment dams continued to improve in size, power, speed, and efficiency as usual. For example, **Figures 23 and 24** (see below and next page) show the construction of New Waddell Dam (1986-1992) and

Figure 23 - New Waddell Dam Construction

the size of the equipment currently used to construct embankment dams. Compare the end-dump truck in **Figure 24** and its 35 yd^3 capacity to the train of 4 yd^3 side-dump cars used to construct Belle Fourche Dam in 1909 shown in **Figure 7**. Also compare the large excavator in **Figure 24** and its 12 yd^3 bucket with steam shovel at Belle Fourche Dam with its 2½-yd^3 bucket shown in **Figure 7**. During Period V, synthetic materials such as high-density polyethylene (HDPE) and polypropylene were developed into new products, such as corrugated pipe, geomembranes, and geotextiles, that were promptly put to use on embankment dams where judged appropriate. New types of equipment related to these new materials and products were developed, and quality control tests, testing equipment, and detailed test procedures were developed, with Reclamation's significant participation in these developments.

Figure 24 - New Waddell Dam - Construction Equipment

Conclusion

The information presented in this paper has summarized the U.S. Bureau of Reclamation's embankment dam design and construction history. During the past century, Reclamation has designed and built some of the most significant embankment dams in the West. Reclamation and its dam engineers produced many successes and a few failures during that period. Reclamation and its civil engineers, through the study of both success and failure and the sharing of the knowledge gained with all professionals worldwide, have indeed played a significant role in the evolution of embankment dam design and construction during the past century. Starting before World War II, Reclamation has provided technical assistance to more than 80 countries and has trained more than 10,000 international colleagues. It is hoped that the lay-person reader of this paper has gained some appreciation of Reclamation's history and just how remarkable the evolution of embankment dam design and construction has been. It is also hoped that the design

and construction engineers reading this paper have gained some understanding of Reclamation's embankment dam design and construction history, and of the reasons for doing all embankment dam work with the utmost knowledge, care, and caution. One of the most important lessons learned from the failure of Teton Dam involved the need for embankment dam designers and construction engineers to work as a team, with their primary concern being the need to design and build the very best and safest dam possible.

REFERENCES

[1] U.S. Department of the Interior, Bureau of Reclamation, Earth Manual, Part 1, 3rd Edition, 1998; and Earth Manual, Part 2, 3rd Edition, 1990.

[2] U.S. Department of the Interior, Bureau of Reclamation, Design of Small Dams, 3rd Edition, 1987.

[3] U.S. Department of the Interior, Bureau of Reclamation, Bureau of Reclamation Historical Organizational Structure, Bureau of Reclamation History Program, Denver, Colorado, 1997.

[4] U.S. Department of the Interior, Bureau of Reclamation, Dams and Public Safety, A Water Resources Technical Publication, by Robert B. Jansen, Revised Reprint 1983.

[5] Eric B. Kollgaard and Wallace L. Chadwick, editors, Development of Dam Engineering in the United States, for the United States Committee of the International Commission on Large Dams, 1988.

[6] U.S. Department of the Interior, Bureau of Reclamation, Design Standards No. 13, EMBANKMENT DAMS, 1986.

[7] U.S. Department of the Interior, Bureau of Reclamation, Development of Earth Dam Design in the Bureau of Reclamation, by F. C. Walker, 1958.

[8] James D. Schuyler, Reservoirs for Irrigation, Eighteenth Annual Report of the United States Geological Survey, Department of the Interior, 1896-1897, Part IV Hydrography, Washington, D.C., U.S. Government Printing Office, 1897, pp. 617-756.

[9] Edward Wegmann, Jr., The Design and Construction of Masonry Dams, John Wiley & Sons, New York, 1888.

[10] Edward Wegmann, Jr., The Design and Construction of Dams, Including Masonry, Earth, Rockfill, Timber and Steel Structures, John Wiley & Sons, New York, 1899.

[11] James Dix Schuyler, Reservoirs for Irrigation, Water-Power and Domestic Water-Supply, John Wiley & Sons, New York, 1901.

[12] James Dix Schuyler, Reservoirs for Irrigation, Water-Power and Domestic Water-Supply, 2nd Edition, John Wiley & Sons, New York, 1909.

[13] Hiram N. Savage, "Flood Overflow of the Sweetwater Dam," Engineering News, August 15, 1895.

[14] R.F. Walter, "The Belle Fourche Dam," Engineering Record, v. 53, pp. 307-10, March 3, 1906.

[15] O.T. Reedy, "Construction of Belle Fourche Dam," Engineering Record, v. 61, pp. 466-69, April 2, 1910.

[16] U.S. Department of the Interior, Bureau of Reclamation, Resident Engineer's Diary - Belle Fourche Dam, 1907-1911.

[17] U.S. Department of the Interior, Bureau of Reclamation, Belle Fourche Project History, 1910-1971.

[18] Richard E. Goodman, Karl Terzaghi - The Engineer As Artist, American Society of Civil Engineers Press, Reston, Virginia, 1999.

[19] J.M. Gaylord and J.L. Savage, High-Pressure Reservoir Outlets - A Report on Bureau of Reclamation Installations, U.S. Government Printing Office, Washington (D.C.), 1923.

[20] U.S. Department of the Interior, Bureau of Reclamation, Dams and Control Works, U.S. Government Printing Office, Washington (D.C.), 1929.

[21] U.S. Department of the Interior, Bureau of Reclamation, Dams and Control Works, U.S. Government Printing Office, Washington (D.C.), 1938, p. 232.

[22] U.S. Department of the Interior, Bureau of Reclamation, Dams and Control Works, U.S. Government Printing Office, Washington (D.C.), 1938.

[23] U.S. Department of the Interior, Bureau of Reclamation, Dams and Control Works, U.S. Government Printing Office, Washington (D.C.), 1938, p. 252.

[24] G.E. Bertram, An Experimental Investigation of Protective Filters, Publications of the Graduate School of Engineering, Harvard University, No. 267, January 1940.

[25] U.S. Department of the Interior, Bureau of Reclamation, The Use of Laboratory Tests to Develop Design Criteria for Protective Filters, Earth Laboratory Report no. EM-425, June 20, 1955.

[26] Elbert E. Esmiol, Seismic Stability of Earth Dams, Technical Memorandum No. 641, U.S. Department of the Interior, Bureau of Reclamation, Branch of Design and Construction, Denver, Colorado, April 1951.

[27] F.C. Walker, Development of Earth Dam Design in the Bureau of Reclamation, U.S. Department of the Interior, Bureau of Reclamation, 1958, p. 18.

[28] James L. Sherard, Richard J. Woodward, Stanley F. Gizienski, and William A. Clevenger, Earth and Earth-Rock Dams, John Wiley and Sons, Inc., New York, 1963, p. 582.

[29] B.P. Bellport, Bureau of Reclamation Experience in Stabilizing Embankment of Fontenelle Earth Dam, Proceedings of the 9th Congress on Large Dams, Istanbul, 1967, pp. 67-79.

[30] B.P. Bellport, Bureau of Reclamation Experience in Stabilizing Embankment of Fontenelle Earth Dam, Proceedings of the 9th Congress on Large Dams, Istanbul, 1967, p. 75.

[31] B.P. Bellport, Bureau of Reclamation Experience in Stabilizing Embankment of Fontenelle Earth Dam, Proceedings of the 9th Congress on Large Dams, Istanbul, 1967, p. 77.

[32] B.P. Bellport, Bureau of Reclamation Experience in Stabilizing Embankment of Fontenelle Earth Dam, Proceedings of the 9th Congress on Large Dams, Istanbul, 1967, p. 78.

[33] U.S. Department of the Interior - Teton Dam Failure Review Group (IRG), Failure of Teton Dam - A Report of Findings, April 1977.

[34] D.J. Duck, R.W. Kramer, and L.W. Davidson, Teton Dam: Summary of Technical Investigations, Proceedings of the 13th ICOLD Congress, New Delhi, India, 1979.

[35] D.J. Duck, R.W. Kramer, and L.W. Davidson, Teton Dam: Summary of Technical Investigations, Proceedings of the 13th ICOLD Congress, New Delhi, India, 1979, p. 7.

[36] Peter P. Aberle, Field Engineer on Teton Dam Construction, Bureau of Reclamation (retired), personal communication, July 2001.

[37] Independent Panel to Review Cause of Teton Dam Failure, Failure of Teton Dam, Report to the Department of the Interior and the State of Idaho, December 1976.

[38] U.S. Department of the Interior - Teton Dam Failure Review Group (IRG), Failure of Teton Dam - Final Report, January 1980.

[39] Comptroller General of the United States, Actions Needed to Increase the Safety of Dams Built by the Bureau of Reclamation and the Corps of Engineers, Genera Accounting Office, Washington, D.C., June 3, 1977.

[40] Comptroller General of the United States, Actions Needed to Increase the Safety of Dams Built by the Bureau of Reclamation and the Corps of Engineers, Genera Accounting Office, Washington, D.C., June 3, 1977, p. 45.

[41] Comptroller General of the United States, Actions Needed to Increase the Safety of Dams Built by the Bureau of Reclamation and the Corps of Engineers, Genera Accounting Office, Washington, D.C., June 3, 1977, p. 61.

[42] W.A. Wahler & Associates, Review of Design, Construction, and Operation of Crystal, Mountain Park, Mt. Elbert Forebay, Nambe Falls, Pueblo, Ririe, and Soldier Creek Dams (actually seven separate reports), for U.S. Department of the Interior Contract No. 14-01-0001-77-C-10, Palo Alto, California, June 1977.

[43] Richard L. Wiltshire, Soldier Creek Dam and Foundation Drainage, Seepage and Leakage from Dams and Impoundments, Proceedings of a Symposium Sponsored by the Geotechnical Engineering Division in Conjunction with the ASCE National Convention, American Society of Civil Engineers, Denver, Colorado, May 5, 1985.

[44] Richard L. Wiltshire, Gordon L. Wind, Chuck R. Cooper, Robert K. McGovern, Walter E. Heyder, and Michael R. Brown, Removal and Reconstruction of McDonald Dam, Flathead Indian Reservation, Montana, Proceedings of the 21st Annual USSD Lecture Series, U.S. Society on Dams, Denver, Colorado, July 30 - August 3, 2001.

[45] U.S. Department of the Interior, Bureau of Reclamation, Embankment Dam Instrumentation Manual, U.S. Government Printing Office, Washington, D.C., January 1987.