FAILURE OF CONCRETE DAMS

by

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INTRODUCTION:

There have been several studies of dam failures published in the last 30 years. Of these, the most comprehensive is the 1983 volume by Jansen[1] published by the U. S. Bureau of Reclamation. That study listed and discussed dam failures that have occurred over the past 900 years. Of the more than 150,000 dams worldwide that represented significant hazards to life or property, only about 2000 have failed over the last 9 centuries, and most of those failures were not major dams.

During the 20th century, there have been about 200 notable failures resulting in the loss of over 8000 lives. Of these 200 dam failures, less than 40 have been concrete or masonry dams.

HISTORICAL FAILURES:

Tables 1 and 2 list information on significant concrete and masonry dam failures. Many of these failed facilities have been successfully rebuilt and are operating in a satisfactory manner. The tables show that (eliminating acts of war) nearly all of

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1)Numbers refer to entries in the Bibliography

TABLE 1

CONCRETE AND MASONRY GRAVITY DAMS

Name of Dam	Location	Height (Ft)	Year of Failure	Age at Failure (Yrs)	Probable Cause of Failure
Alla Sella Zerbino	Italy	39	1935	12	Foundation seepage, sliding, and overturning
Austin	Pennsylvania	50	1911	1.8	Foundation sliding and concrete cracking
Bouzey (masonry)	France	72	1895	14	Uplift and internal hydrostatic pressures
Dujeprostroj	Russia	131	1941	unknown	Destroyed in war
Eder	Germany	157	1943	29	Destroyed in war
Eigiau	Wales	35	1925	17	Seepage under dam
Khadakwasla (masonry)	India	131	1961	82	Uplift pressures and internal cracking
Mohne	Germany	132	1943	32	Destroyed in war
Puentes (masonry)	Spain	164	1802	11	Seepage under dam
Tigra (masonry)	India	86	1917	0.25	Overtopping and sliding

TABLE 2

CONCRETE DAMS OTHER THAN GRAVITY TYPE

Name of Dam	Location	Height (Ft)	Year of Failure	Age at Failure (Yrs)	Probable Cause of Failure
Gleno[1]	Italy	143	1923	0.5	Poor design and workmanship
Malpasset[2]	France	200	1959	5	Weak abutment rock, high water pressure in abutment
St. Francis[3]	California	205	1928	2	Poor foundation, internal cracking
Vaiont[4]	Italy	869	1963	3	Overtopping caused by rockslide in reservoir
Vega de Tera[5]	Spain	112	1959	2	Leakage in joints, foundation sliding

1 - Multiple arch and gravity

2 - Arch

3 - Arched/gravity

4 - Arch

5 - Buttress, masonry, and slab

these failures resulted either directly or indirectly from foundation or abutment problems.

The fact that there are many more failures of earth dams than concrete dams is primarily due to three factors: (1) There are many more earth dams; (2) Concrete dams are typically built on more stable foundations; and (3) Concrete is an inherently stronger material than earth fill.

Concrete dam failures do, however, occur and typically result in massive property damage and significant loss of life.

FAILURE CLASSIFICATION:

It is important to distinguish between types of failure. The failure may be either structural or functional (or both). A structural failure refers to active failure by cracking, breaking, sliding or overturning such that the dam itself is damaged, while a functional failure refers to a condition wherein the dam is no longer able to perform its function (i.e. retain water). Structural failures commonly are very newsworthy and typically result in damage downstream, while functional failures usually are scheduled for repair or modifications. Functional failures include situations such as excessive seepage, malfunctioning valves or gates, etc. A functional failure can become a structural failure and all structural failures are also functional failures.

EVIDENCES OF DEFICIENCIES:

Common evidences of deficiencies in concrete dams include:

1. <u>Stress and Strain</u> - Cracks, crushing, or offsets in concrete monoliths, buttresses, face slabs, arch barrels, galleries, operating chambers, and conduits: stress and temperature cracking patterns in buttresses, pilasters, diaphragms, and arch barrels: or stress decline in posttensioned anchorages and tendons.
2. <u>Instability</u> - Excessive or unevenly distributed uplift pressures; different movement of adjacent monoliths, buttresses, arch barrels, or face slabs; movement along construction joints; or uplift on horizontal lift surfaces revealed by seepage on downstream face or in galleries.
3. <u>Seepage at Discontinuites</u> - Embankment wraparound sections, waterstops in monoliths and face slabs, or reservoir impounding backfill at spillway control sections and retaining walls.
4. <u>Foundations and Abutments</u> - Piping of material from solution channels or rock joints; clogged drains; movement at faults or shear zones; sliding along bedding planes; or consolidation of weak strata due to the mass of the dam and reservoir, or in a horizontal plane due to thrust from an arch dam.

<u>FACTORS OF IMPORTANCE</u>:

It is believed that factors of greatest importance to the safety of the two principal types of concrete dams are as follows:

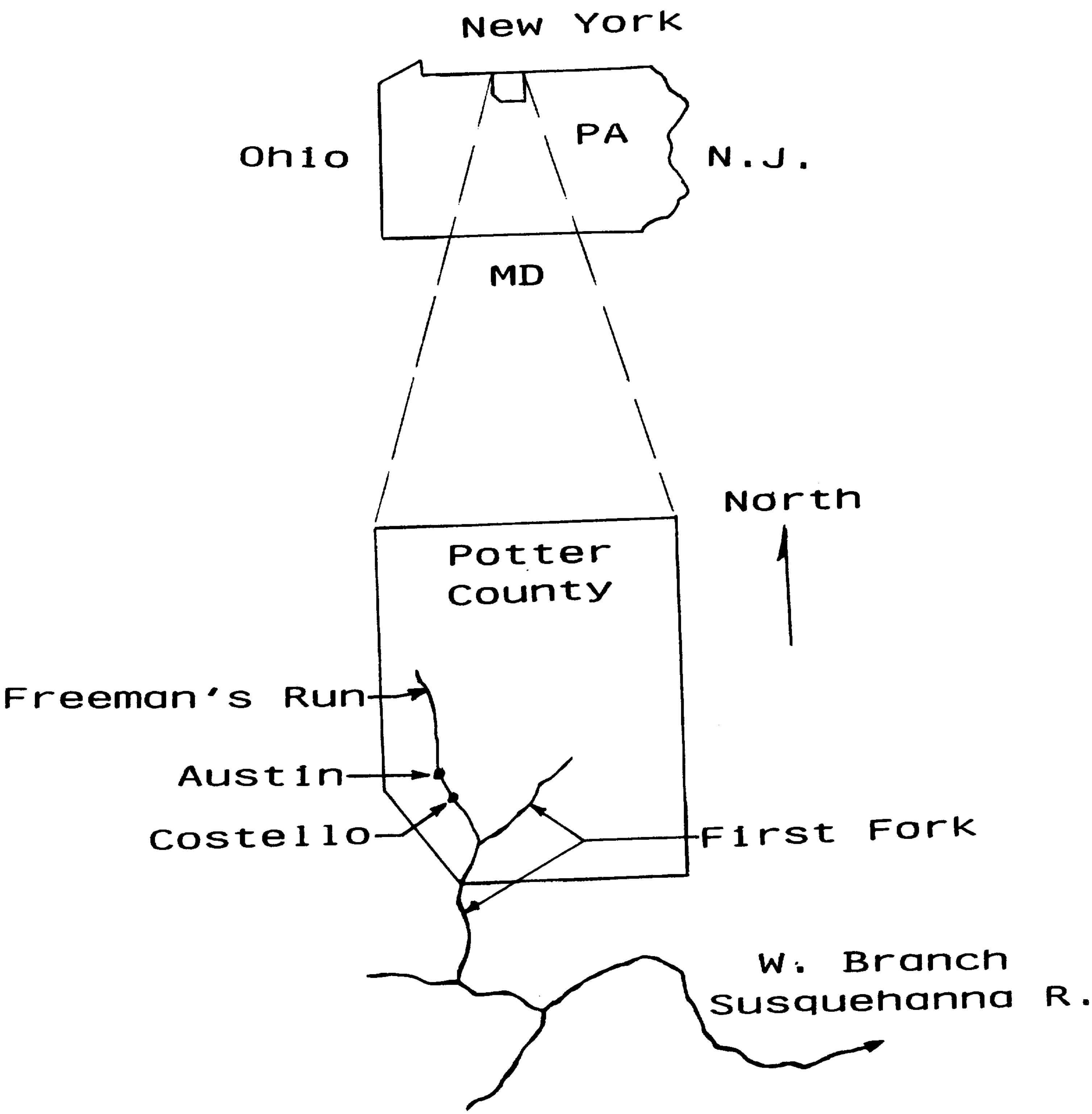
1. <u>Concrete Arch Dams</u> - Because of the monolithic behavior of arch dams, horizontal displacement due to arching thrust forces against the abutments is of great importance. Also important are seepage flows, foundation movement and relative movement at any joint in the dam or foundation.

2. <u>Concrete Gravity Dams</u> - It is important for a gravity or buttress dam to maintain its structural integrity and remain stable against sliding. Relative movement at joints and cracks, seepage flows, and hydrostatic uplift are also very important.

<u>EXAMPLE - AUSTIN DAM</u>:

As indicated in Tables 1 and 2, only two major failures of concrete dams in the United States have resulted in significant loss of life and massive property damage. Those dams are the St. Francis Dam in California which failed in 1928 resulting in the loss of 450 lives and the Austin Dam in Pennsylvania which failed in 1911 with about 80 lives lost. Much has been written about the St. Francis failure, but relatively litte attention has been paid to the Austin Dam failure. A detailed discussion of that failure follows.

Austin Dam is located in western Potter County in north-central Pennsylvania as shown in Figure 1. The dam was built across Freeman's Run in mountainous terrain about 1.5 miles north of the town of Austin. The town of Costello is located about 3 miles south of Austin. Freeman's Run has a drainage area of



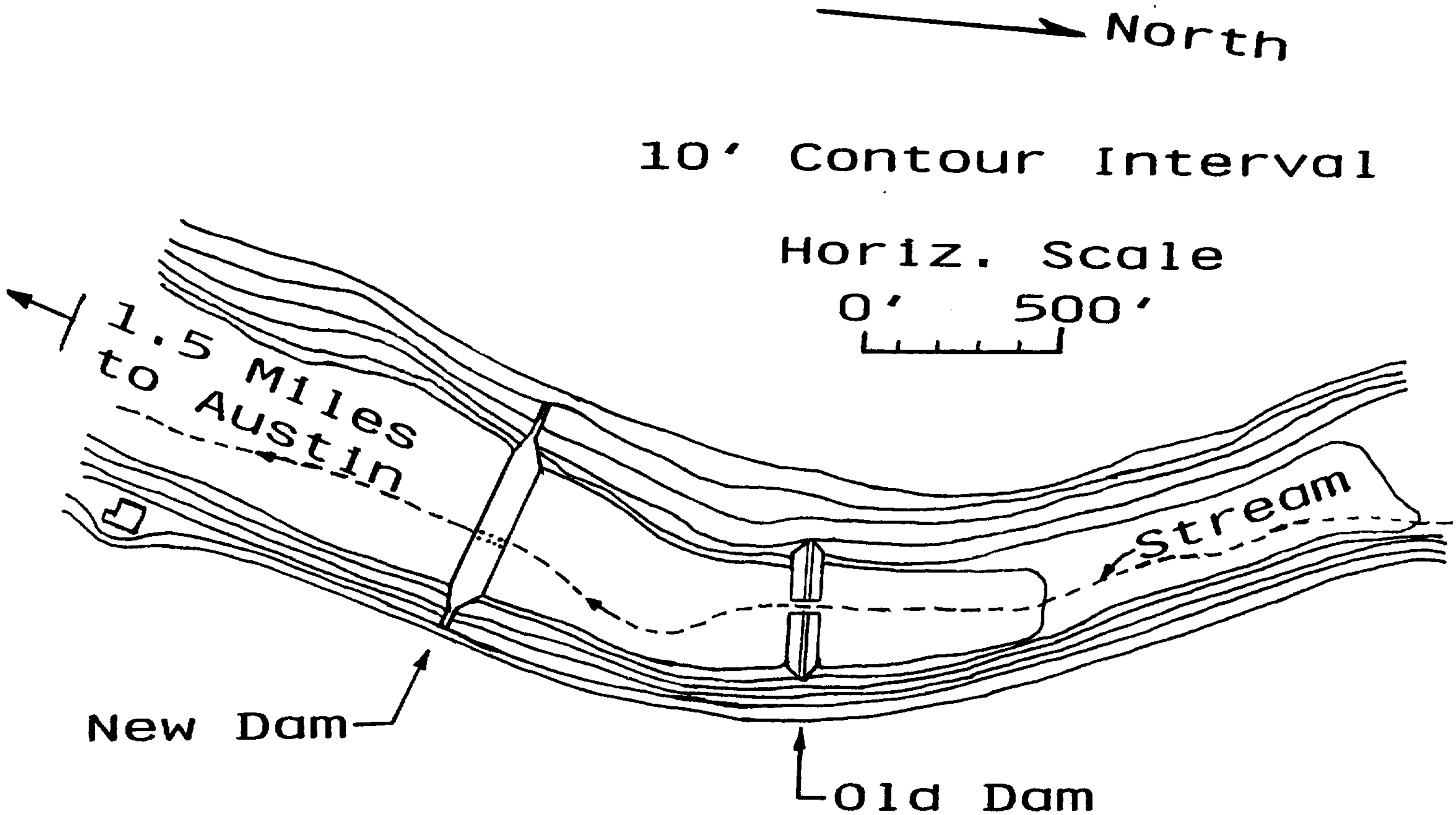
LOCATION MAP

FIG. 1

about 35 square miles upstream from the dam. Waters from Freeman's Run eventually enter the Susquehanna River and then flow to Chesapeake Bay.

As shown in Figure 2, an earlier dam was built on Freeman's Run in 1899. This old dam was about 20 feet high and was constructed of timber grillage filled with rock and soil and then topped with compacted earth. The old dam impounded about 25 million gallons of water for use at the Bayless Pulp and Paper Co. Mill located in the valley between the dam and the town of Austin. The valley walls are relatively steep, rising about two hundred feet above the valley floor. The Bayless Co. needed additional water reserves for dry weather, so in 1909, Mr. T. Chalkley Hatton, a noted engineer from Wilmington, Delaware was hired to design a new high dam to impound at least 200 million gallons of water. The dam was designed and construction was completed on Dec. 1, 1909. Statistics on the dam are given in Table 3. This data was obtained from an Engineering News[2] article published in 1910.

It is interesting to note that the original design called for an 8-foot deep keyway, but the owner, in an effort to reduce costs reduced the size to only 4 feet. The designer then required the compacted earth fill on the upstream face in an attempt to reduce underseepage. The foundation rock was hard sandstone, but contained many thin interbedded shale layers which appeared to soften rapidly when exposed to free water. The foundation was cleaned to a hard sandstone surface prior to placement of concrete. Good workmanship was reported.



DAM CONFIGURATION

FIG. 2

TABLE 3

DAM STATISTICS

Length - 544 feet

Height (above valley floor) - 49 feet

Spilling - overflow 2 feet below crest

Emergency drainage - 36 inch pipe (capped)

Foundation - sandstone with interbedded shale

Keyway - 4 feet wide, 4 feet deep

Grouting - none (embankment upstream)

Concrete - 15780 cubic yards (lower portion cyclopean)

Excavation - 7925 cubic yards

Cost - $71,821 (plus engineering)

It is also interesting to note that, in order to save money, the emergency drain pipe was not fitted with a valve or gate, but was simply capped. Reinforcement consisted of a few one-half inch bars in the upper upstream face and some 1.25 inch bars extending into the foundation rock presumably to serve as anchors. In the lower portion of the dam, large quarry stones up to 2 cubic yards in size were placed in the concrete such that a minimum of 6 inches of concrete surrounded them. Concrete was mixed on both sides of the valley and carried out on the dam. During construction, a labor strike occurred when the dam was about two-thirds completed. A week later, over 100 laborers were brought in from New York City to finish the project.

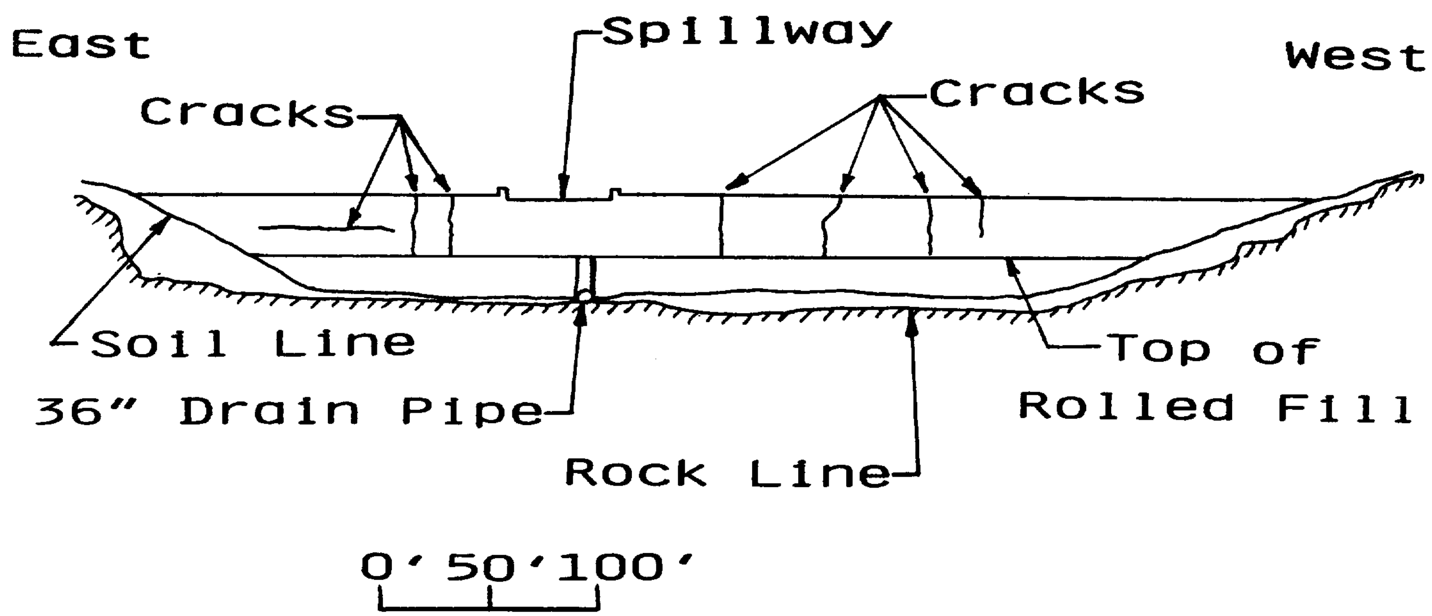
Figure 3 shows the completed dam, while Figure 4 shows cross-sections through the dam. As seen in Figure 3, at least 6 vertical cracks were noted in the dam soon after completion. The cracks were blamed on concrete shrinkage. One horizontal crack east of the spillway likely represents the "cold" joint which occurred during the labor strike.

Less than two months after the completion of the dam, during the third week of January, 1910, the weather grew warm and heavy rain fell melting an unusually thick snow cover. Within 3 days, the dam filled to overflowing, which occurred on Saturday, January 21. On Sunday, January 22, a large slice of earth adjacent to the downstream side of the east abutment slid into the valley. Water began emerging from at least 3 locations from 15 to 50 feet downstream of the toe of the dam. However, due to

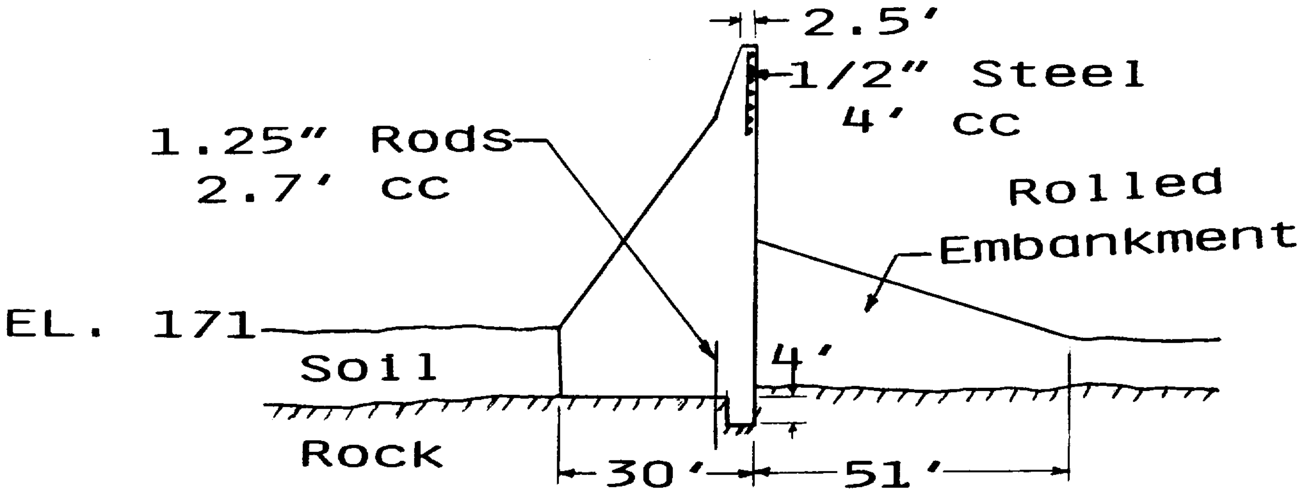
FIG. 3

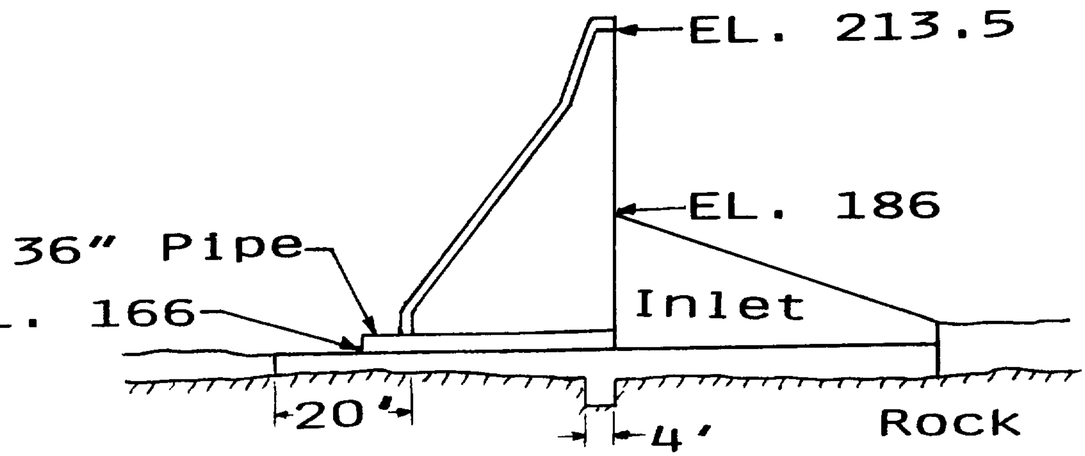
ELEVATION-UPSTREAM

END OF CONSTRUCTION



X - SECTION





X-SECTION (SPILLWAY)

FIG. 4

the fact that the drainage pipe had been capped rather than gated, the reservoir could not be lowered.

The company decided in this emergency that the water level must be lowered, so dynamite was used to blow holes at two locations in the top of the dam; one at the west abutment and one just east of the spillway. This effort succeeded in lowering the water level only about four feet, so dynamite was lowered to the top of the drainage pipe and the cap was blasted off. The entire reservoir then drained in about 16 hours.

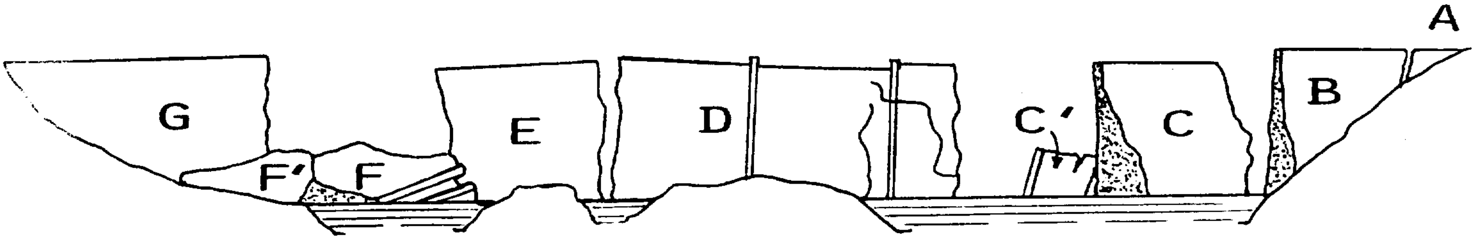
The dam was then thoroughly inspected and it was found that no cracking had occurred in the concrete foundation. It had simply slid (probably on a soft shale layer) downstream. The vertical anchor rods were intact, but the rock in which they were embedded had moved. It was obvious that the uplift hydrostatic pressure due to seepage below the dam reduced the factor of safety against sliding to less than 1.0. The consultant recommended repairing the dam's concrete, sealing the cracks, the construction of a massive stone buttress on the downstream side, and the construction of an upstream cutoff trench. The company decided to repair the concrete which had been blasted, do some crack sealing, replace abutment fill and recap the drainage pipe. No other alterations were made. Within a month after repairs, the dam was nearly full again and it was again observed that over 600 gallons/minute seepage was occurring.

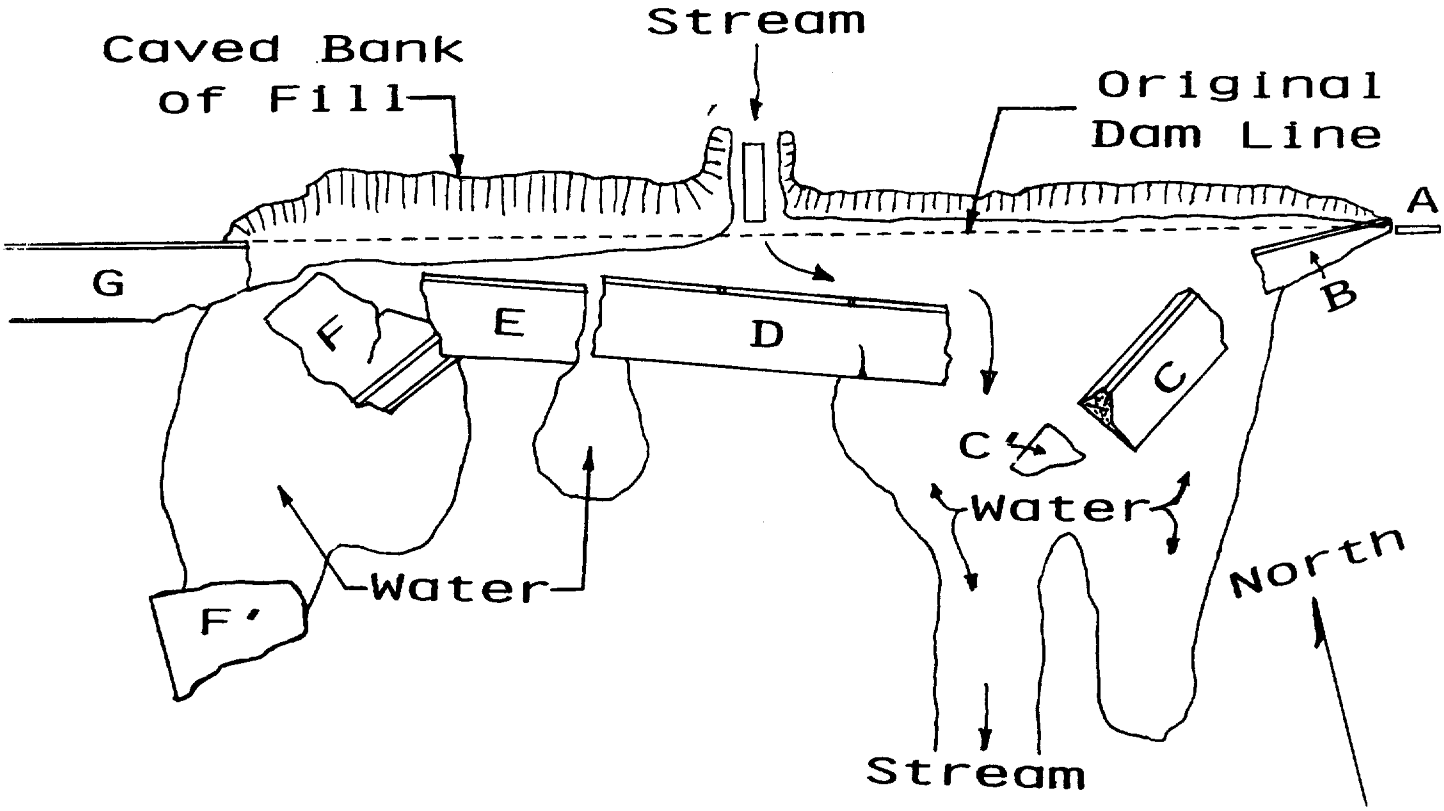
Relatively dry weather was then prevalent for over 1.5 years until the month of September, 1911, when unusually heavy rains completely filled the reservoir. At that time, the Bayless Mill had an entire summer's cutting of pulp wood stacked at the mill upstream from Austin. These thousands of cords of wood added greatly to the destructive effects of the flood which was to come.

The dam break occurred between 2:00 and 2:30 p.m. on a calm Saturday afternoon, September 30, 1911. The dam collapse is described in an account in the Engineering News[3] issue of October 5, 1911. The appearance of the dam did not suggest a gradual failure, but a telephone warning from a nearby house did allow some residents of Austin to flee to safety on the hillsides. The reported failure sequence was that a small segment of the dam west of the spillway "blew" out first, and almost simultaneously a section east of the spillway cracked and swung downstream. (The towns of Austin and Costello were destroyed with at least 78 lives lost.) Figure 5 shows an elevation of the broken dam and a plan view showing the distortion of the failed structure.

An unusual feature of this dam is that now, almost 78 years after the break, the ruins of the dam still stand just as they did at the time of the failure. Some concrete spalling has occurred, but it is easy to identify the fragments and to reconstruct the failure. No attempt was ever made to rebuild the dam or to clean up the site. Soil and shale fragments still lie as they were pushed upward downstream from the sections that slid. Depending upon the values used for shearing strength of the soft shale, the safety factor against sliding may be computed between 0.6 and 1.0.

ELEVATION-DOWNSTREAM





PLAN VIEW

FIG. 5

LESSONS LEARNED:

The failure of the Austin Dam presents excellent examples of several major problems including:

1) No thorough foundation investigation.
2) Construction did not follow design criteria.
3) No water cutoff below dam.
4) No easy way to lower reservoir in emergency.
5) Anchor rods did not "anchor".
6) Repair recommendations were not followed.
7) At least one "cold" joint present in dam.
8) Safety factor not sufficient against sliding.
9) Full water pressure against dam less than 2 months after completion.

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2. Engineering News, "The Partial Failure of a Concrete Dam at Austin, Pennsylvania", McGraw Publishing Co., New York City, March 17, 1910.

3. Engineering News, "The Failure of a Concrete Dam at Austin, Pennsylvania", McGraw Publishing Co., New York City, October 5, 1911.