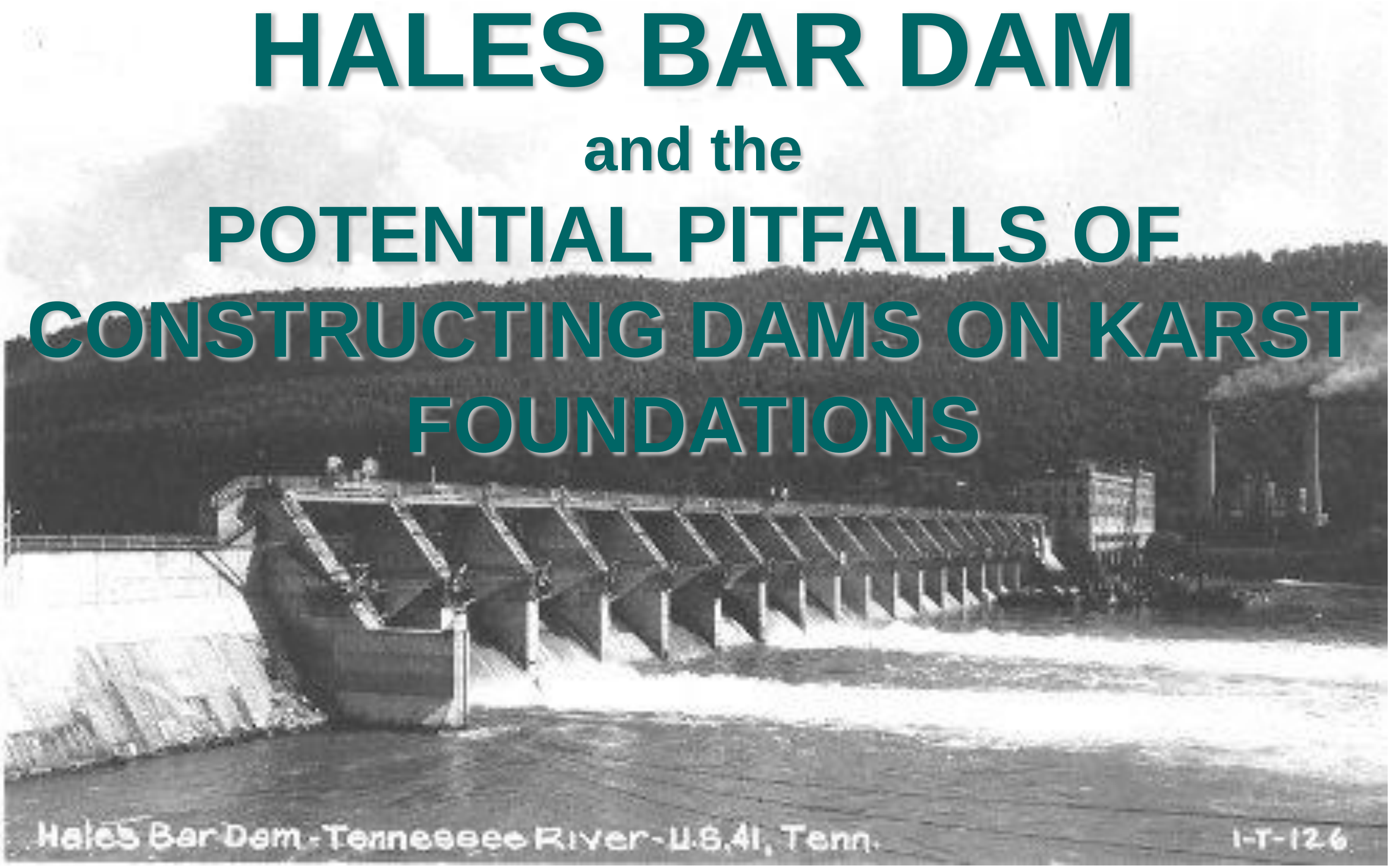
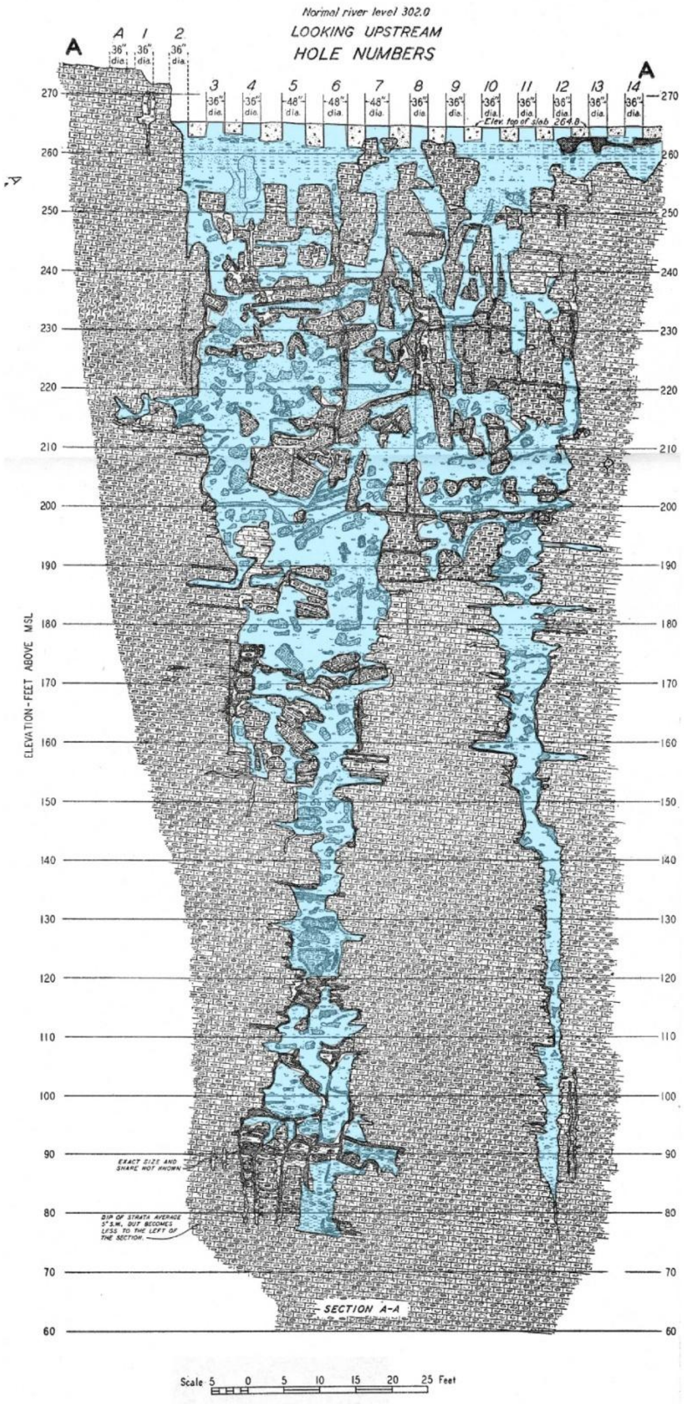
HALES BAR DAM

and the

POTENTIAL PITFALLS OF CONSTRUCTING DAMS ON KARST FOUNDATIONS



J. David Rogers, Ph.D., P.E., P.G.
Missouri University of Science & Technology
for the symposium on



Karst foundations are always problematic

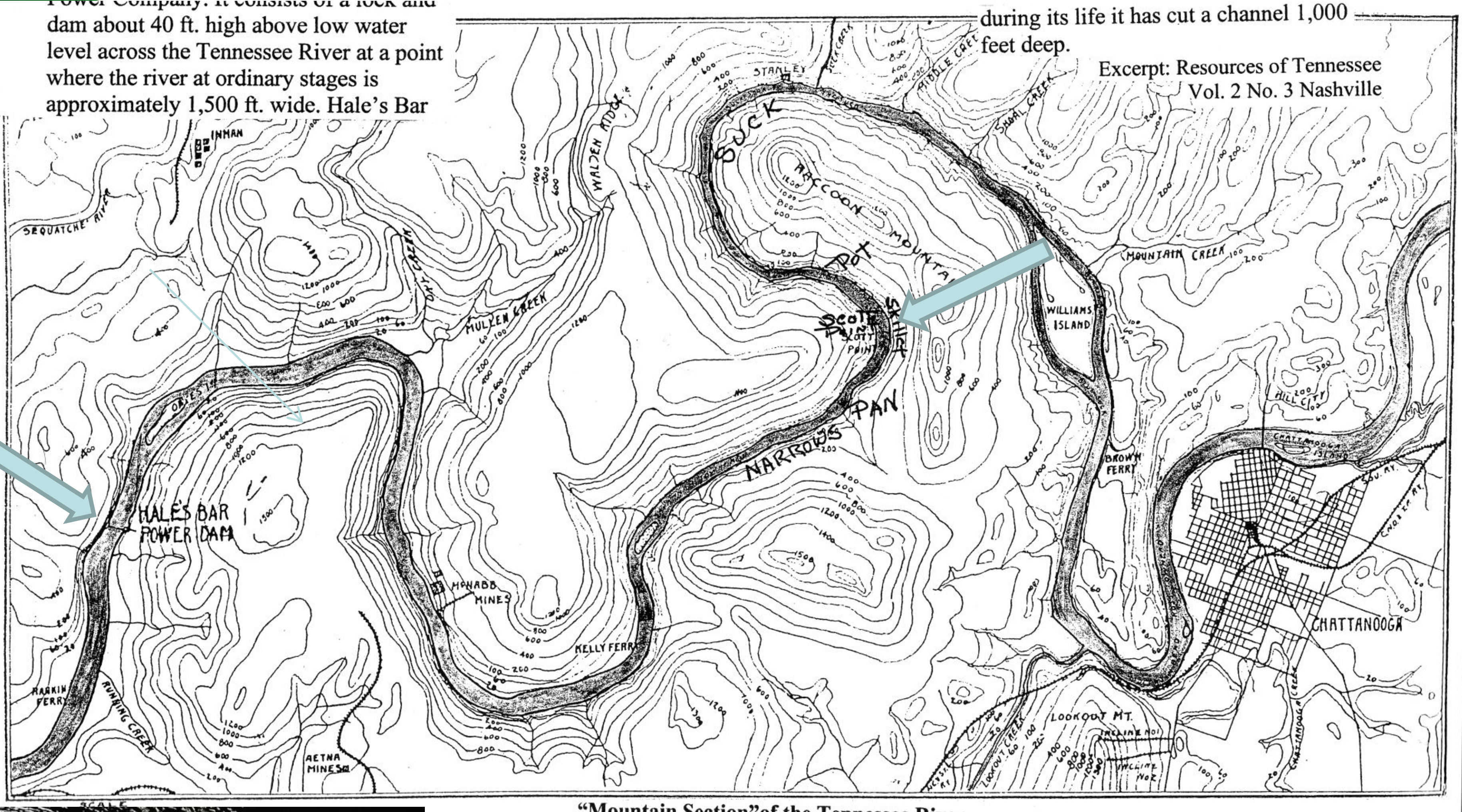
- This section illustrates the cavernous ground explored beneath the foundations for the Kentucky Dam, near the mouth of the Kentucky River, about 20 miles east of Paducah, Kentucky in the early 1940s
- Caverns extended up to 200 feet below river level, 70 feet below the channel thalweg!
- The foundation treatment required almost 800,000 cubic feet of cement grout, a record in 1943.

- The Tennessee River Gorge is located immediately downstream of Chattanooga. It is known as the *Grand Canyon of Tennessee River*. It contained a number of perilous "suck holes," where swirling currents in the tight turns of the river obstructed riverine navigation.

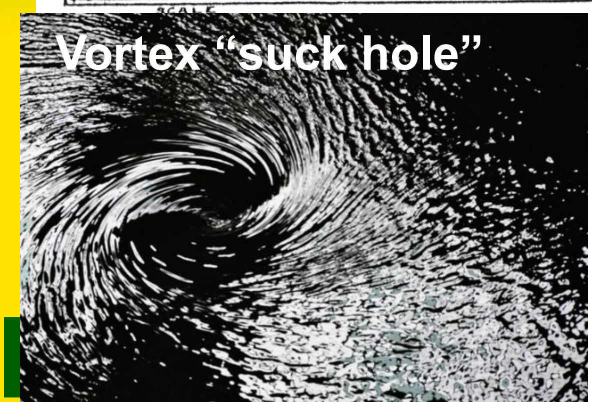
Power Company. It consists of a lock and dam about 40 ft. high above low water level across the Tennessee River at a point where the river at ordinary stages is approximately 1,500 ft. wide. Hale's Bar

during its life it has cut a channel 1,000 feet deep.

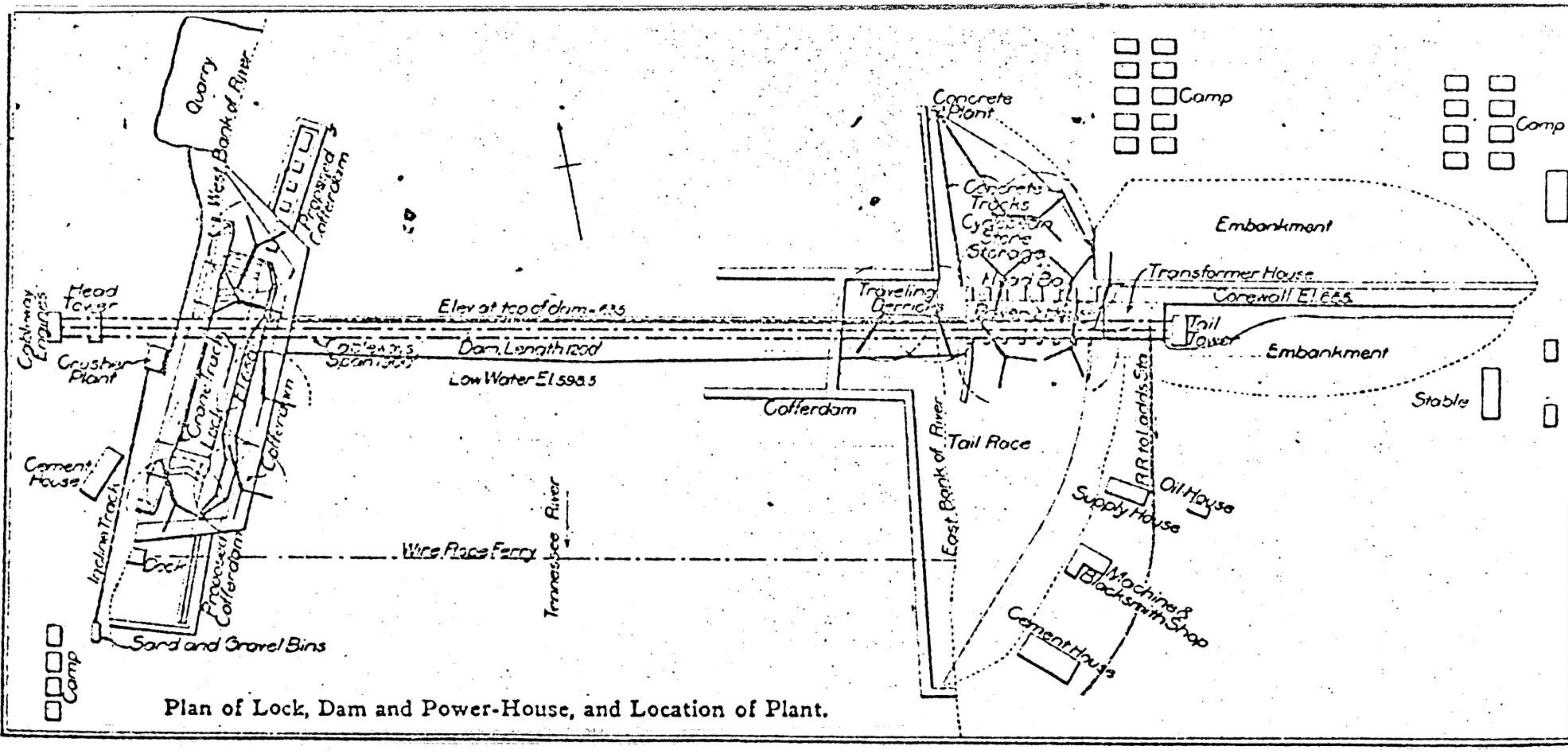
Excerpt: Resources of Tennessee Vol. 2 No. 3 Nashville



“Mountain Section” of the Tennessee River

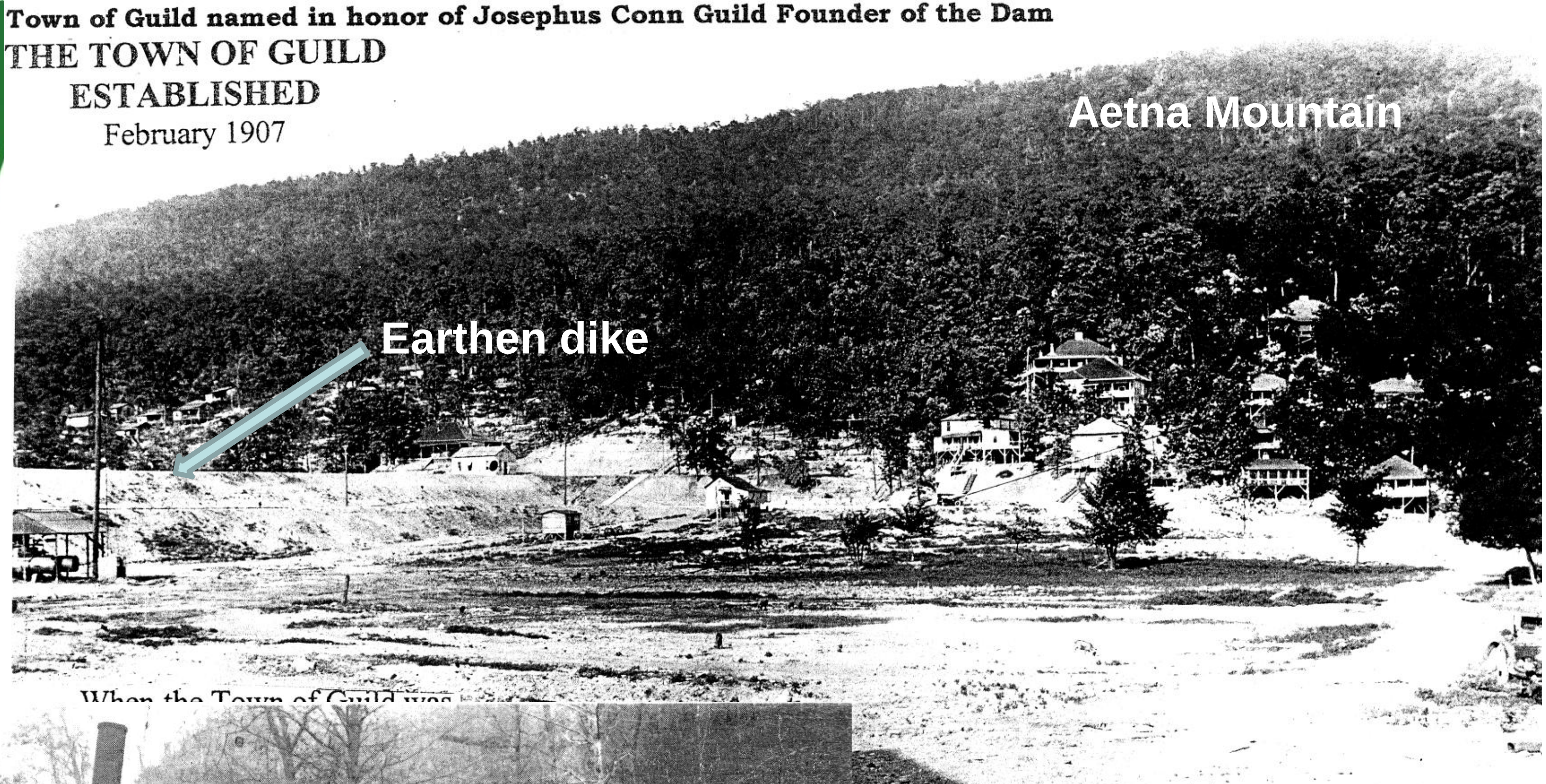


- The original dam site was at Scott Point, but a dam here would not inundate the lower gorge and its pool would impact Chattanooga. A site 33 river miles below the city was then selected, at Hales Bar.
- Image at left shows a “suck hole” (vortex)



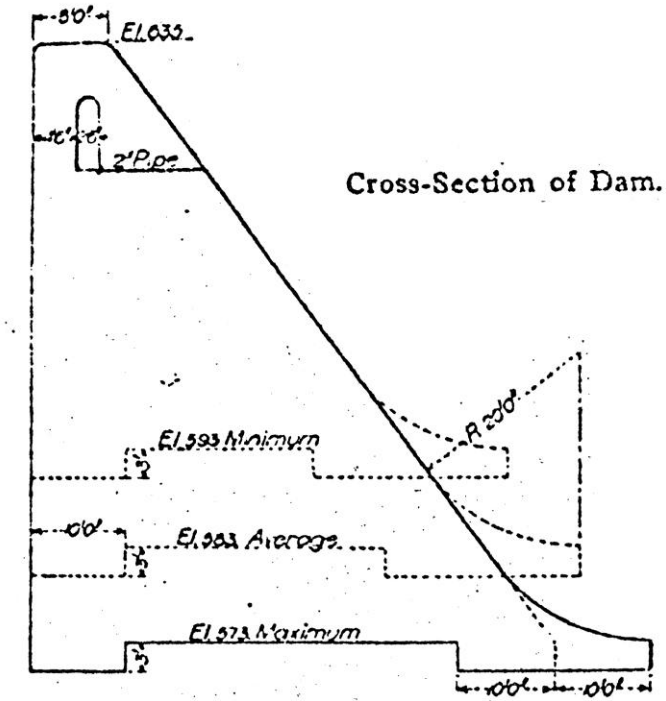
Plan of Lock, Dam and Power-House, and Location of Plant.

- **The Hales Bar dam site was chosen downstream in 1904, solely on the basis of favorable topography, at the southwest end of the Tennessee River Gorge. It was built by the Chattanooga and Tennessee River Power Company between 1905-13, to develop hydroelectric power.**
- **With a width of 2,315 ft., it was a pioneering design for its era; with a concrete dike overflow section 1300 ft long, the highest single lift lock in the world, a sizable powerhouse, and an earthen dike with embedded concrete core wall. The geology was completely ignored.**



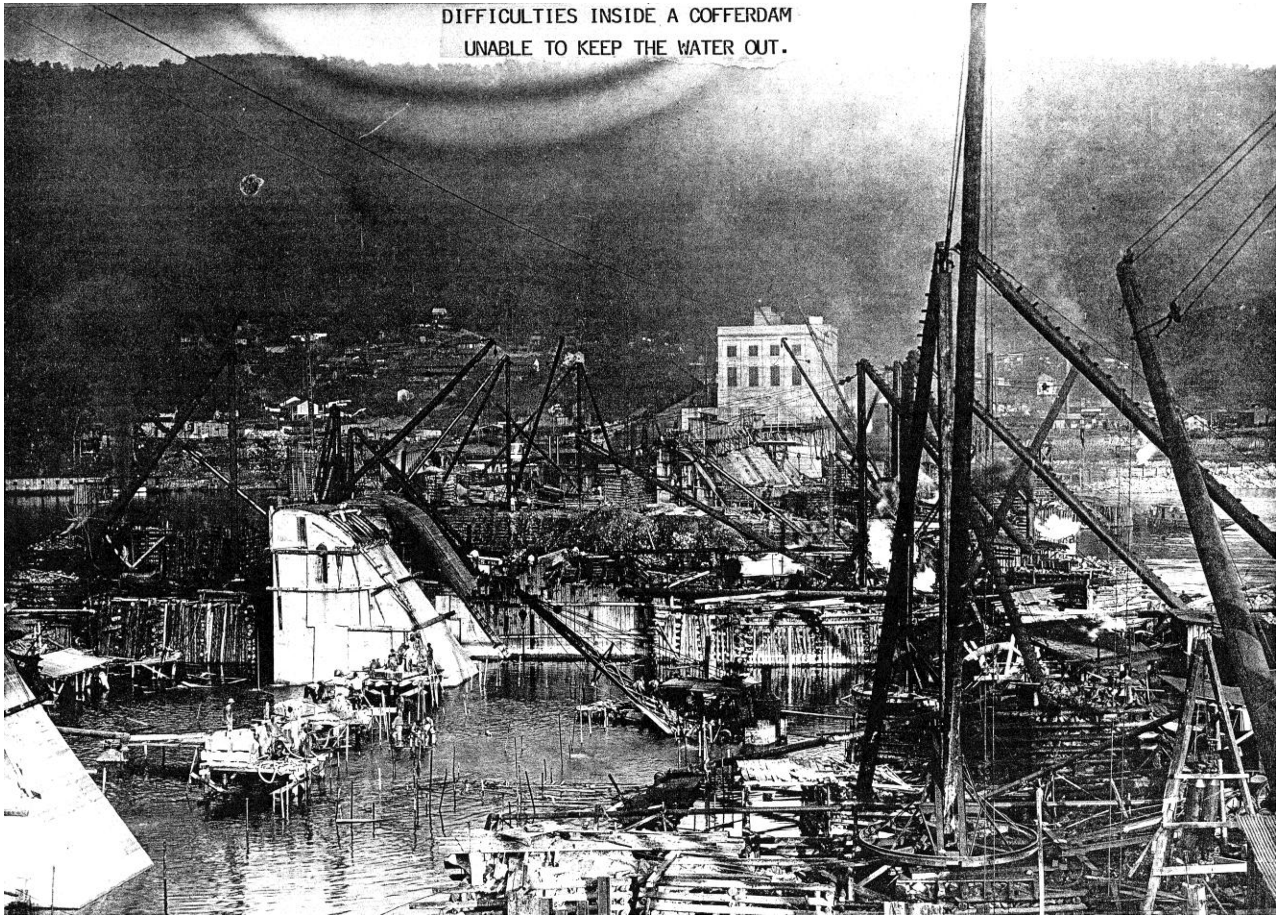
- **In October 1905 W.J. Oliver Co. of New York brought two Bucyrus steam shovels to the site and began work on the 100,000 cubic yard earthen dike, 75 ft high, placed around with a 10,000 cubic yard concrete core wall, 7 to 85 ft high.**
- **Oliver's bid was for $1.5 million, in a 2-year contract. The job would eventually cost over $10 million to complete, and took 8 years to complete**

General aspects of the design



The main overflow weir portion of the dam was to be 1200 ft wide, rising 59 to 113 feet above the river bed (originally believed to be 45 to 65 ft). A triangular section was adopted, with an interior gallery, which would subsequently proved invaluable.

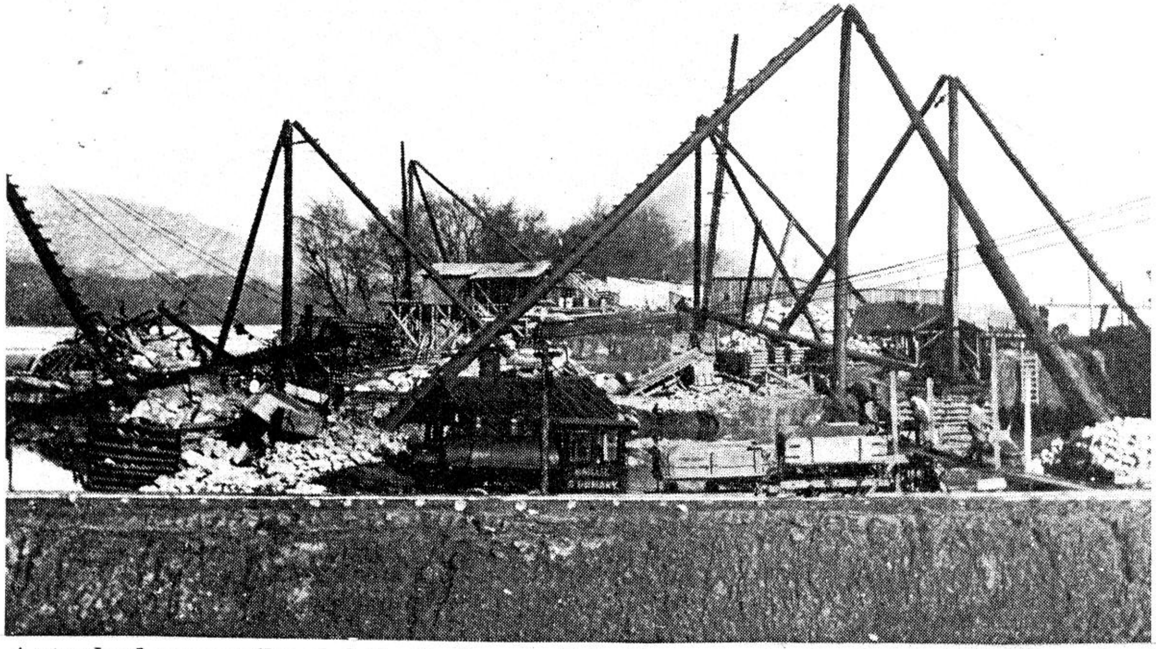
- The concrete structures required 1,000 rail car loads of cement, 150,000 cubic yards of rock, and 500,000 cubic yards of foundation excavation.
- 900,000 cubic yards of soil was eventually excavated, as well as 175,000 cubic yards of rock.
- No one foresaw the underseepage problems, which were unprecedented.



- **In 1906 Oliver attempted his first cofferdam and encountered great difficulty. In November 1907 he abandoned the job.**
- **T.J. Shea took over the job, but they failed to conquer the underseepage problems, and walked off the job in March 1908.**
- **In March 1908 Ballie-Dumary started work, then Flaharty, both abandoning the project in December 1909.**

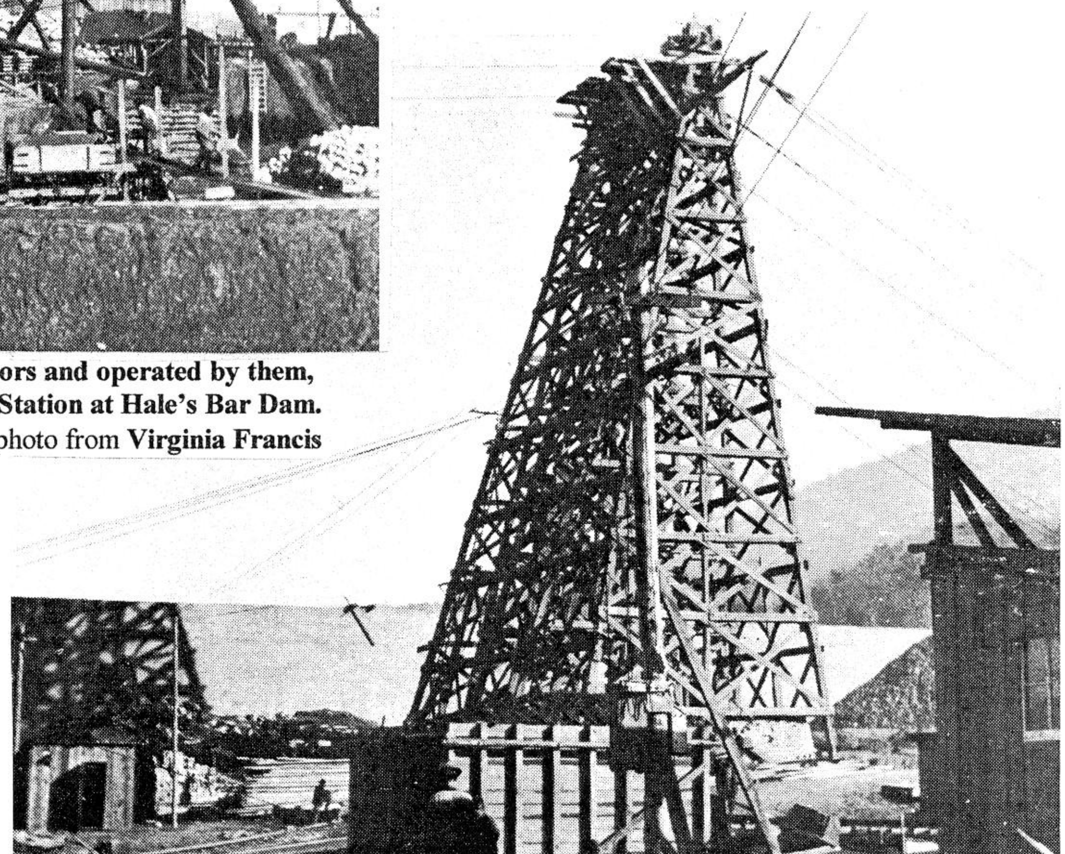
STIFF LEG DERRICKS AND TRANSMISSION LINES AT HALE'S BAR -1909

The camps, power plants, cement storage & concrete mixing plants are installed on both sides of the river. Shops, store houses, offices, stables and several camps, commissaries & many dwellings for employees are in place. & communication between them is afforded by the cableway & by the wire-rope ferry about 1,400 ft. long which is operated by an engine installed on a boat.



A standard gauge railroad, 3 ½ miles long, built by the contractors and operated by them, with a 40 ton Rogers locomotive connects the works with Ladd Station at Hale's Bar Dam.
April 17, 1909 photo from **Virginia Francis**

The plant required, most of which is now installed, includes sections of cofferdam having a combined length of about 5,380 ft.; a triple cableway across the river over the main dam, several miles of standard-gauge track for connection to the main lines & service at the dam.
Two power plants, a large equipment of locomotives, cars, derricks, hoisting engines, drills and other machinery.
Two fixed & one movable concrete plants, Stone for the cyclopean rock & for the concrete is obtained from a quarry at an elevation of about 60 ft above the water level & 500 ft. upstream from the dam, and is delivered to the concrete mixers and to the cableways by boats and by dump cars drawn by a locomotive on a standard track.



Work at Hales Bar 1909 **photos from Virginia Francis**

Construction Difficulties

- Between 1905-10 four different contractors failed to complete the project because of difficult foundation conditions.
- The engineering firm of Jacobs and Davis completed the project on a time-and- materials basis between 1910-13, by employing 2-inch and 6-inch diameter diamond drill core holes for exploration and a series of reinforced concrete caissons 40x45 ft on upstream side and 30x32 ft on the downstream side.

- **In January 1910 Jacobs & Davis began work as the 5th contractor on the troubled dam, completing their first caisson in January 1910, using compressed air pressure of 25 psi.**
- **In 1911 they began drilling reinforced concrete caissons and undertaking extensive grouting, using 6-inch diameter holes extended 30 to 50 ft into the rock foundation in the worst areas.**
- **2-inch diameter grout holes were used elsewhere.**

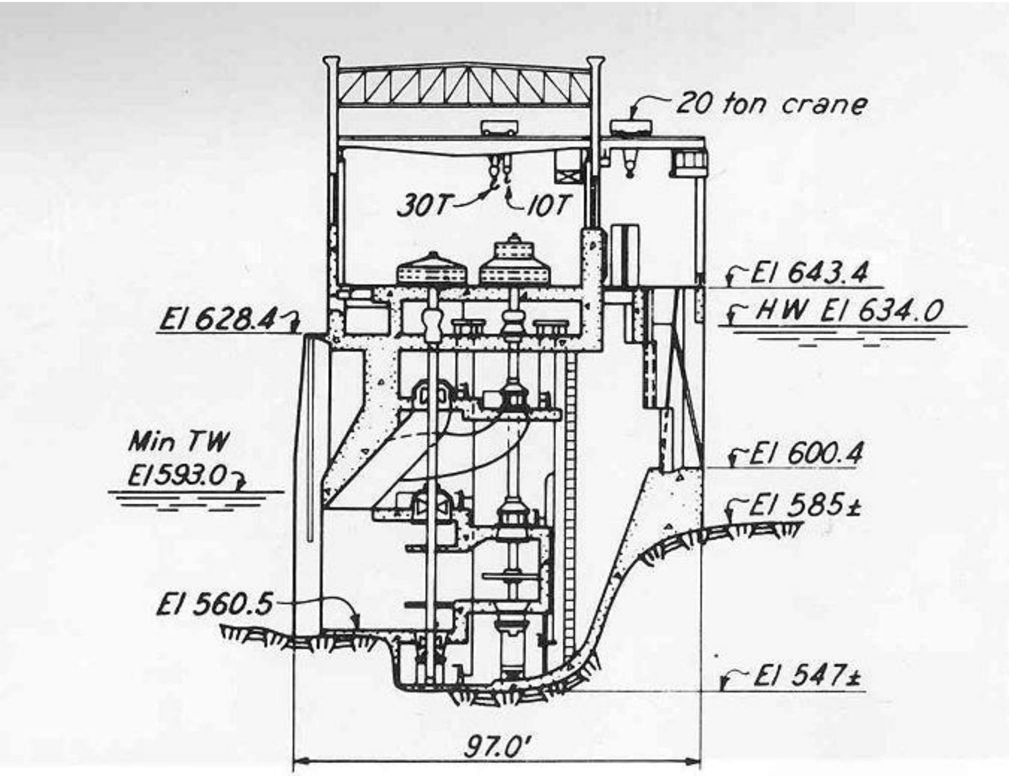
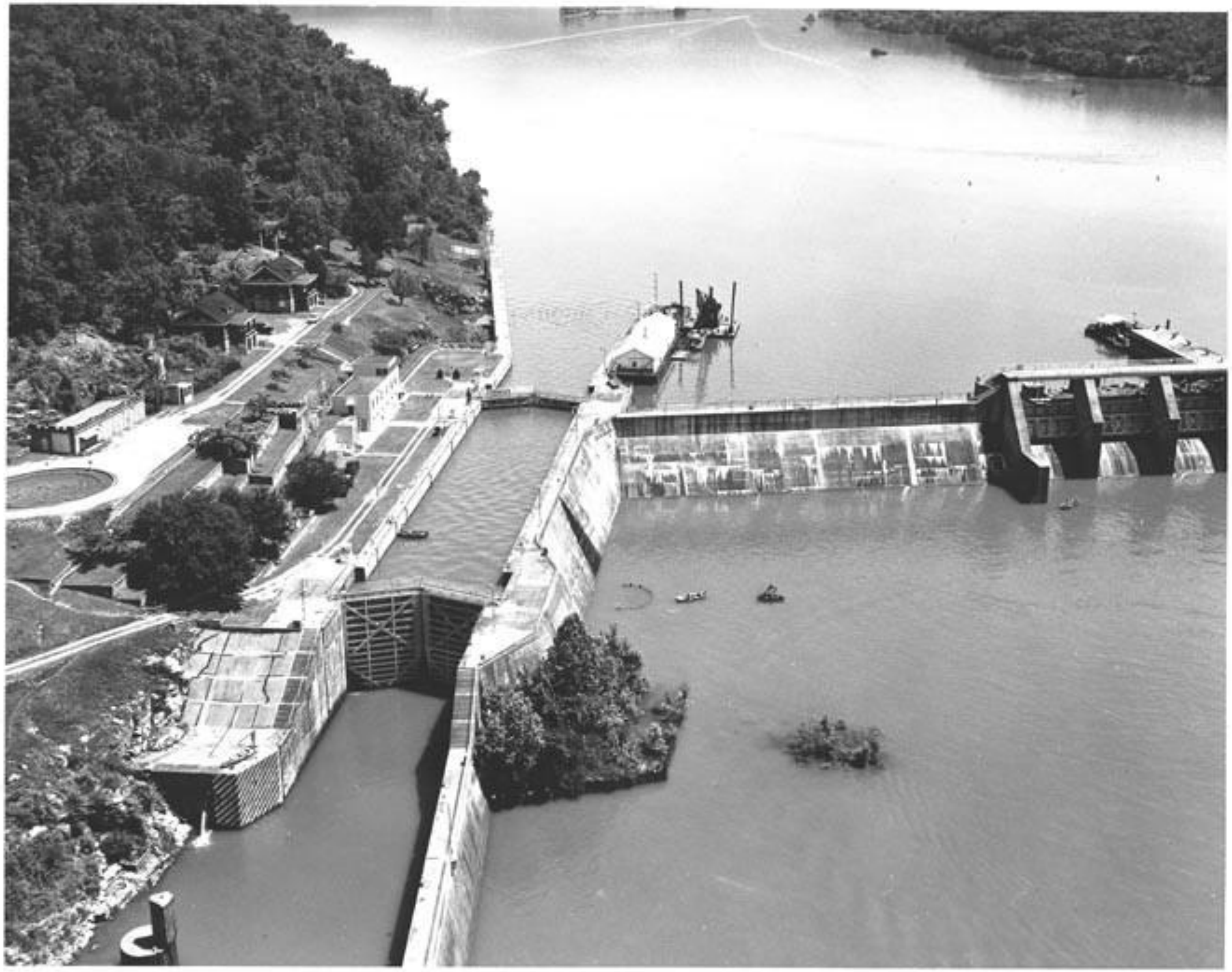


FIGURE 6.—*Hales Bar units 1-8—cross sectional view of unit, showing arrangement of triple-runner-type turbine.*

- **The powerhouse employed a 98 x 240 ft substructure which extended 75 ft below the original river bed, and 96 ft below the main generator floor. It employed an operating pressure head of 41 feet, and was completed in November 1913.**



- **41 ft lift lock on the right (west) bank of Hales Bar Dam was the first built across a navigable river in the USA, as well as being the highest when it opened in 1913. Just 265 ft long, it soon became the shortest lock on the Tennessee River.**

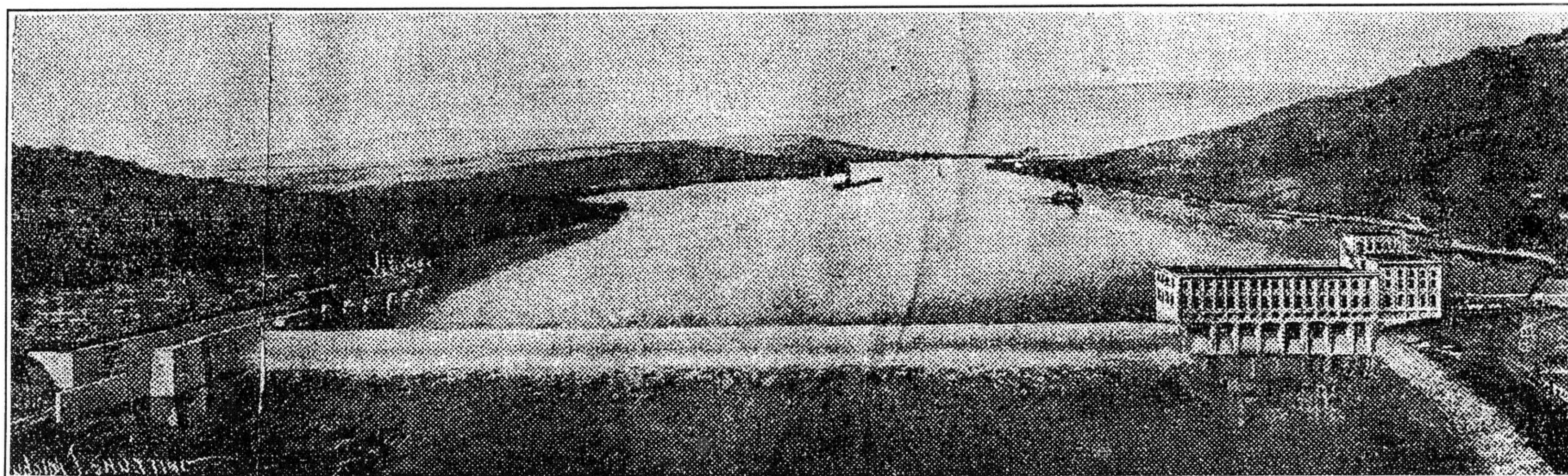
CITY OF CHATTANOOGA ENTERS UPON ELECTRICAL ERA

Tennessee River's Strength Converted Into Hydro-Electric Power in Dedication of Great $10,000,000 Plant

THE CHATTANOOGA NEWS

V0L. XXVI. No. 116 | 4 O'CLOCK EDITION | CHATTANOOGA, TENNESSEE | Thursday NOVEMBER 13, 1913 | Two Cents

VIEW OF GOVERNMENT LOCK, DAM AND POWERHOUSE IN THE DISTANCE

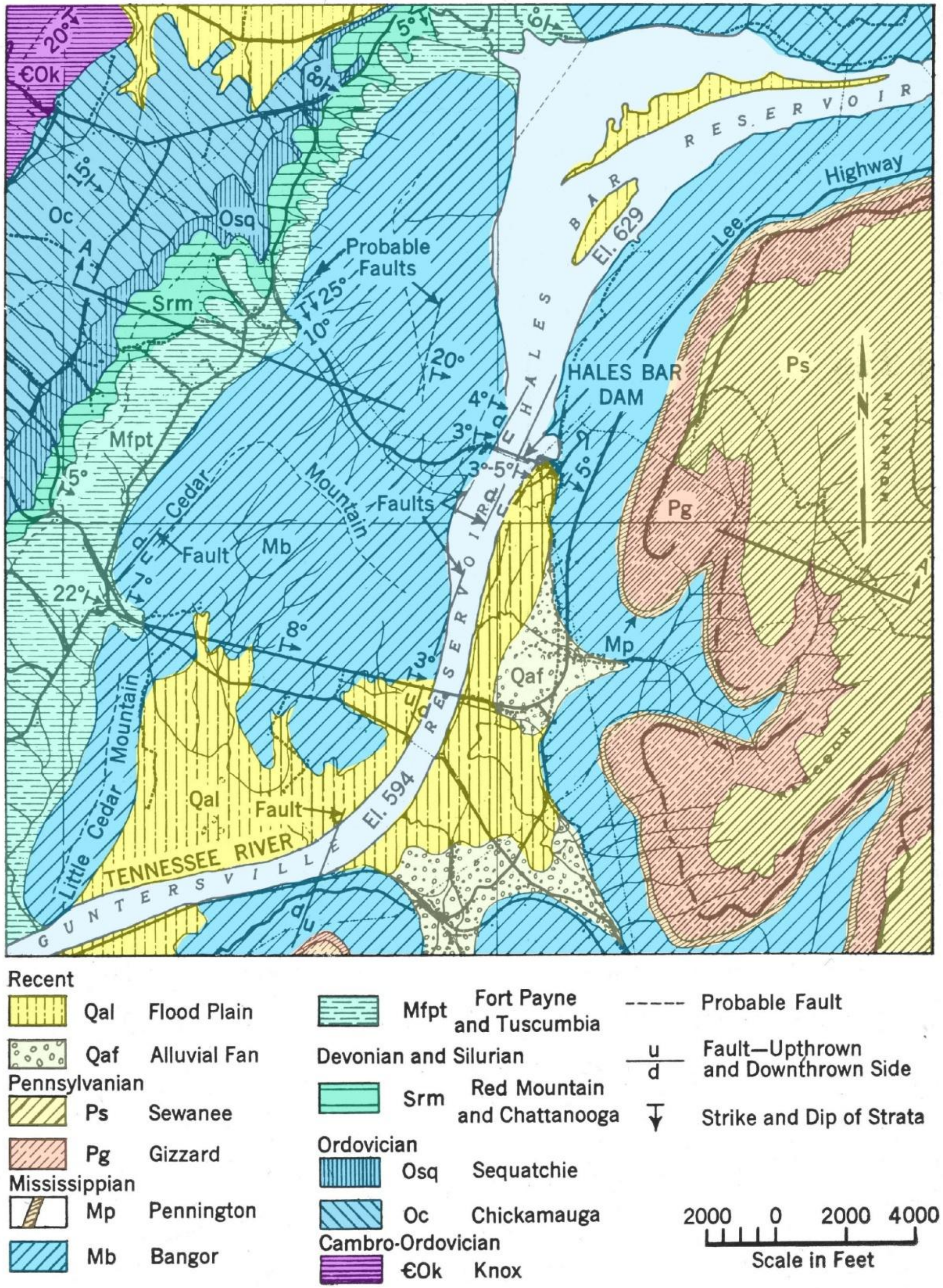


Here can be seen the Completed Dam as it appeared before the Water Began to Pour Over it – In the Foreground is the Lock through which Steamers Will Pass. The Lock is 59 Feet High.

- **The dam, lock, and powerhouse were officially completed in November 1913, and electrical power conveyed to Chattanooga.**
- **Man had finally conquered nature…**

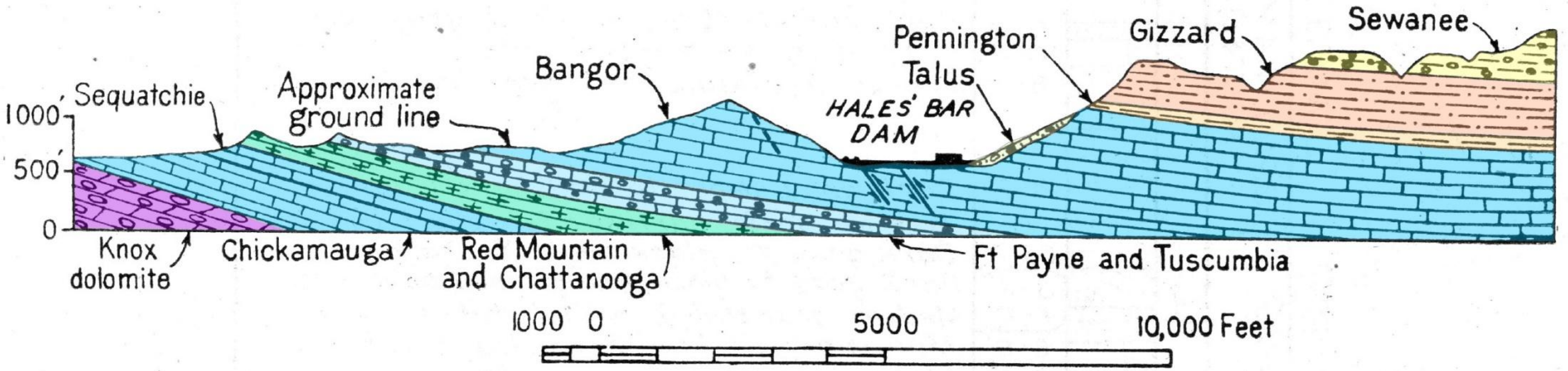
- **The project required congressional approval because it was the first time a private power company constructed a major dam across a navigable channel in the United States!**
- **Soon after completion wooden flashboards were tacked into the crest to increase the operating pool from 636 to 639 ft, shown here in the 1920s.**

Geology

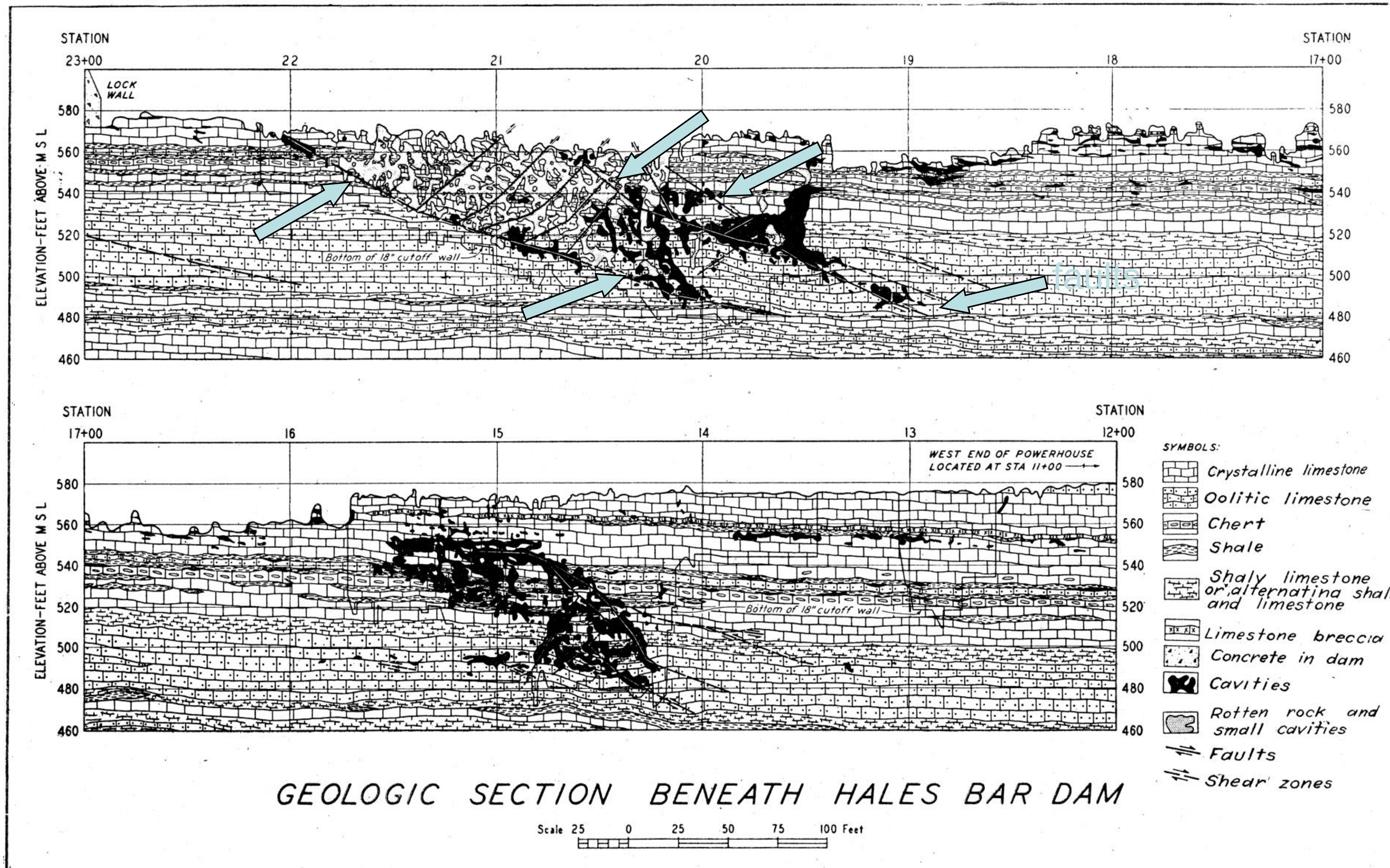


- **Everyone assumed that the narrow channel at the dam site meant more resistant rock comprised the foundations.**
- **Mississippian age Bangor Limestone**

Geologic Setting – Hales Bar Dam



- The dam site was located on the Tennessee River about 33 miles downstream of Chattanooga in the Cumberland Plateau Province, on the southeast flank of the Sequatchie Anticline, towards the downstream end of the Walden Ridge Gorge.
- This was the narrowest reach of the river for many miles
- The narrow, crooked, and shallow channel was structurally controlled by two faults in the Mississippian age Bangor Limestone.



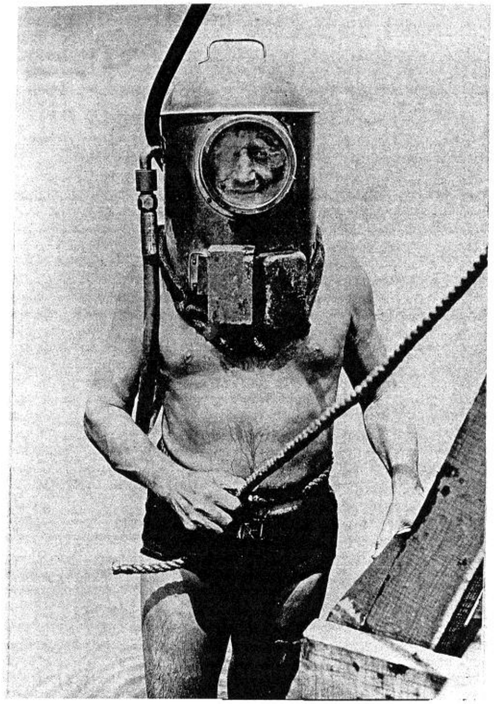
- After 25 years of study, it was learned that the **Bangor limestone** contained numerous **clay-filled cavities** (shown in white) and open **interconnected caverns,** shown in black. The clay-filled cavities proved to be the unsolvable problem, not the open caverns.

Early Attempts to Stem Leakage

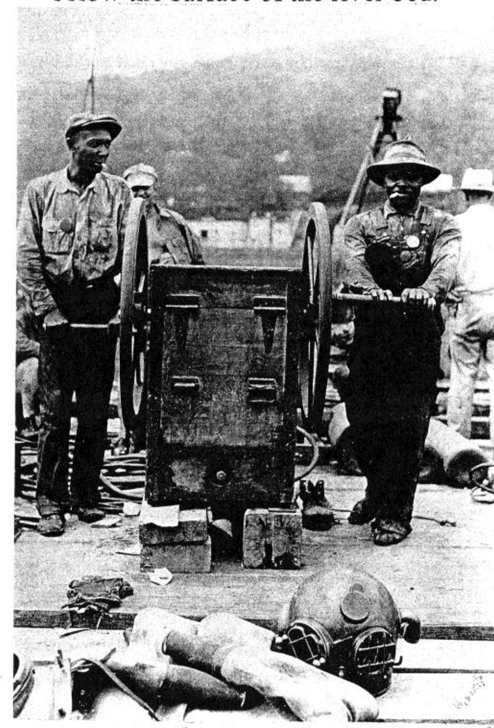
- Shortly after completion excessive leakage around the eastern abutment was combated using dumped rock, but the leakage only increased. Soundings were made in 1914 to determine the areas of gross leakage
- In 1915 rags were placed over suction holes on the river bed below the dam and concrete was pumped over these
- Once a leak was stemmed, leakage would resume at other, adjacent locations
- They tried stemming the leak holes in the river bed using hay bales, old mattresses, chicken wire, and even carloads of corsets!

EXCAVATIONS MUST GO 50 FEET UNDER THE RIVER

Even after the work is started there will be many different features of the job to consider. In building the dam excavation will have to be made 50 feet under the river bed before solid rock is struck. It is said that there is a layer of sand fifty feet deep under the river through which the water penetrates. All of this sand will have to be removed in the immediate section of the dam, as the water would work under a cofferdam through the sand unless the shells went clear through to solid rock. Before the work on the dam can start, the river will have to be pumped dry of the water in the immediate vicinity of the section of which the dam is being constructed. Appliances and machinery will have to be put in place, which will prevent any section of the coffer dam from giving away and catching the men who are working on the foundations of the dam, fifty feet below the surface of the river bed.



Dillan Hemstread was the main diver at the Time of building the Dam. Diving to get the base (tiles) etc, in the proper place.

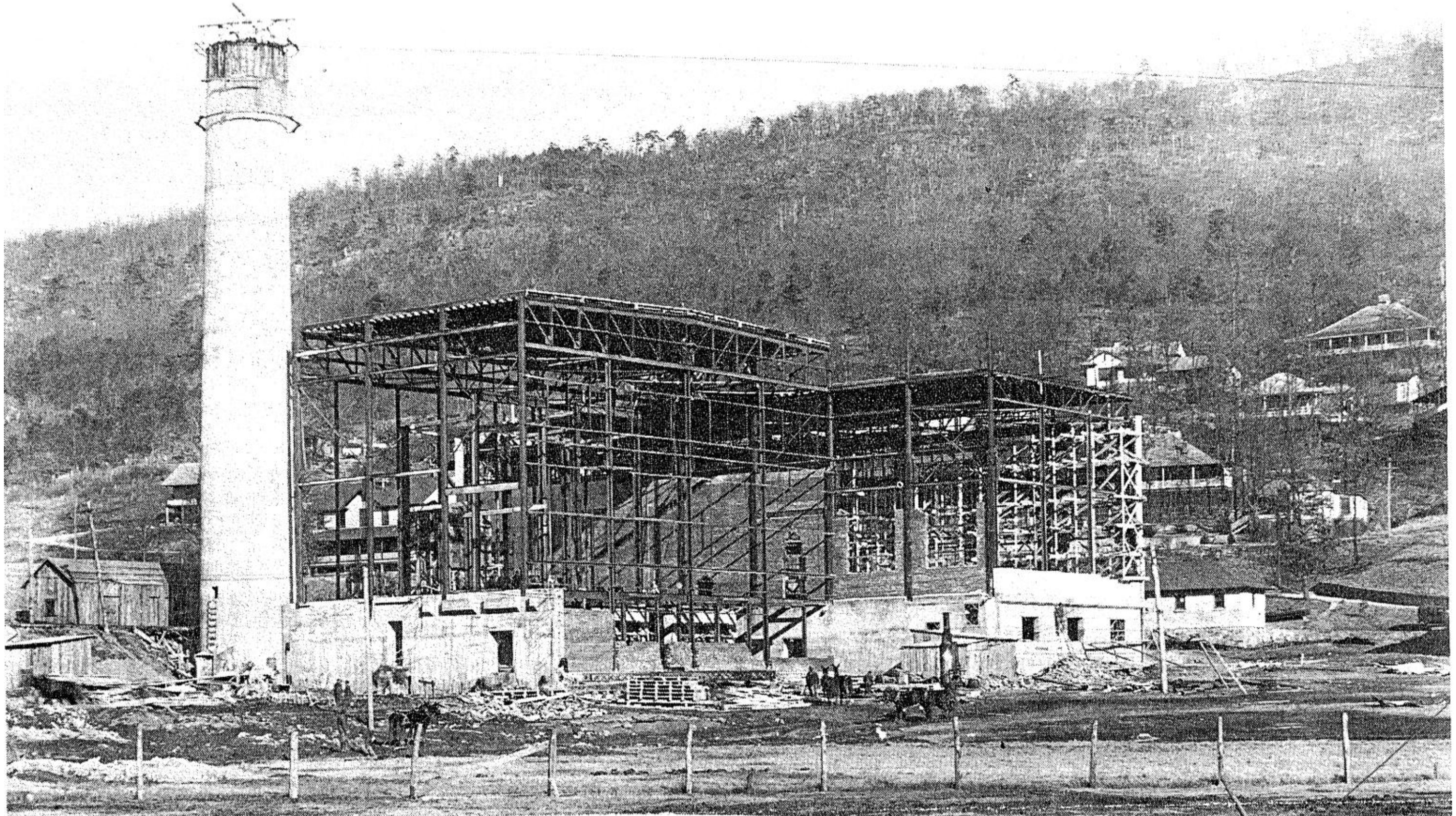


Greatest Care Necessary at All Times.

- **The project pioneered the use of divers in locating the leaks, both up and downstream of the new dam. In 1915-19 rags were dropped into suck holes and covered with tremied concrete.**

Asphalt Grouting Program

- In 1919 the owners began drilling grout holes from inspection gallery inside the concrete dam and pumping hot asphalt into the foundation voids
- This allowed plugging agent to be injected into running water, with an injection pressure as high as 200 psi
- They injected 78,324 cu ft of hot asphalt grout into the dam foundation
- Total drilling footage was 6,266 lineal feet, with average hole depth of 92 ft
- By 1922 it appeared that this program of leakage control had succeeded !



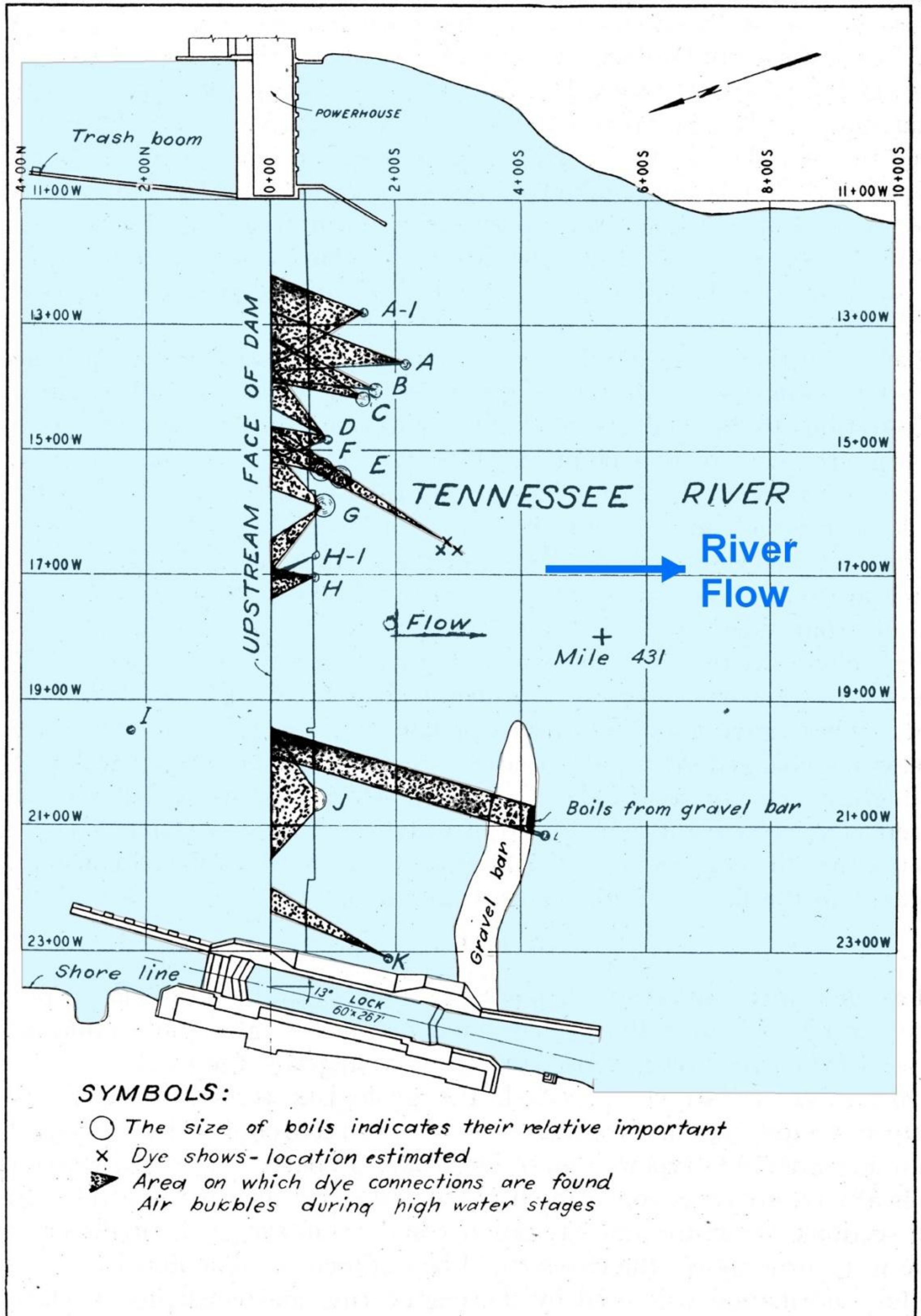
Hales Bar Steam Plant Under Construction 1923

Jo Conn Guild Photographic Collection

- **In 1922-24 a new coal-fired steam power plant was constructed along the river's left bank, with two prominent stacks.**

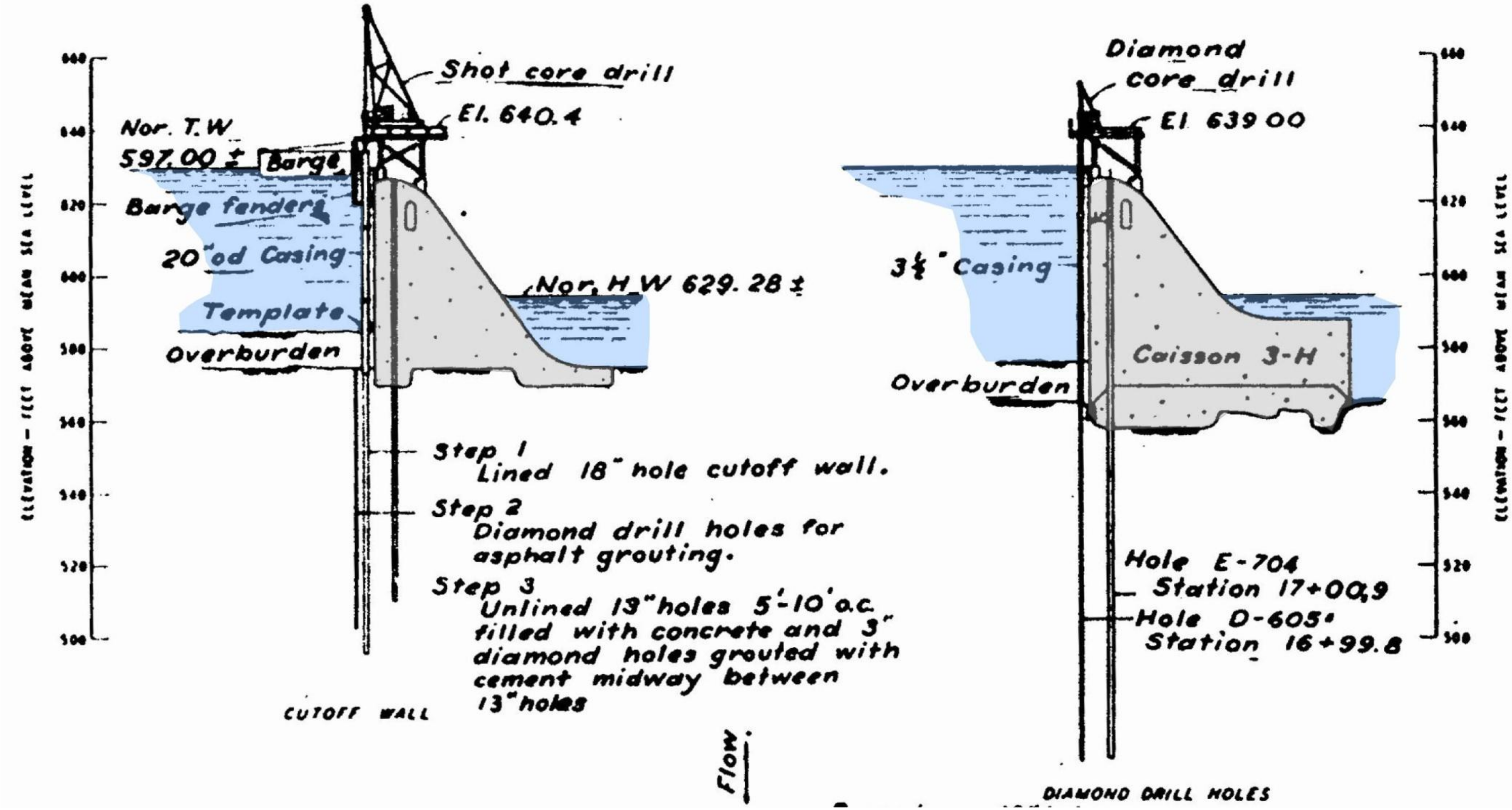
Leakage Problems Resume

- Excess leakage gradually resumed between 1922-29, rising to as great a level as had been observed in 1919
- The asphalt grouting program was only effective in the uppermost portion of the grout holes, seldom penetrating beyond 10 or 15 feet.
- In 1930-31 a thorough program of exploration was undertaken, using dyes and oils to identify flow conduits developed under the dam.
- Leakage was determined to vary between 100 and 1200 cubic feet per second (cfs)



Seepage Conduits

- Flourescein dyes were used in measurements of seepage by the USGS and the TVA in 1939
- These revealed that the leakage beneath the main dam varied between 1720 and 1650 cfs; about 10% of the Tennessee River's normal flow
- In plan view at left, note seepage boils formed in the gravel bar, which increased each year, to 13 known boils by mid 1939



- The Tennessee Valley Authority purchased the dam in August 1939 and began investigating the problems in November 1940, using 3-inch diameter diamond drill holes along the upstream face of the dam and it's overflow section (shown here)
- The seepage cutoff wall was subsequently drilled along the dam's centerline, downstream of the diamond drill holes

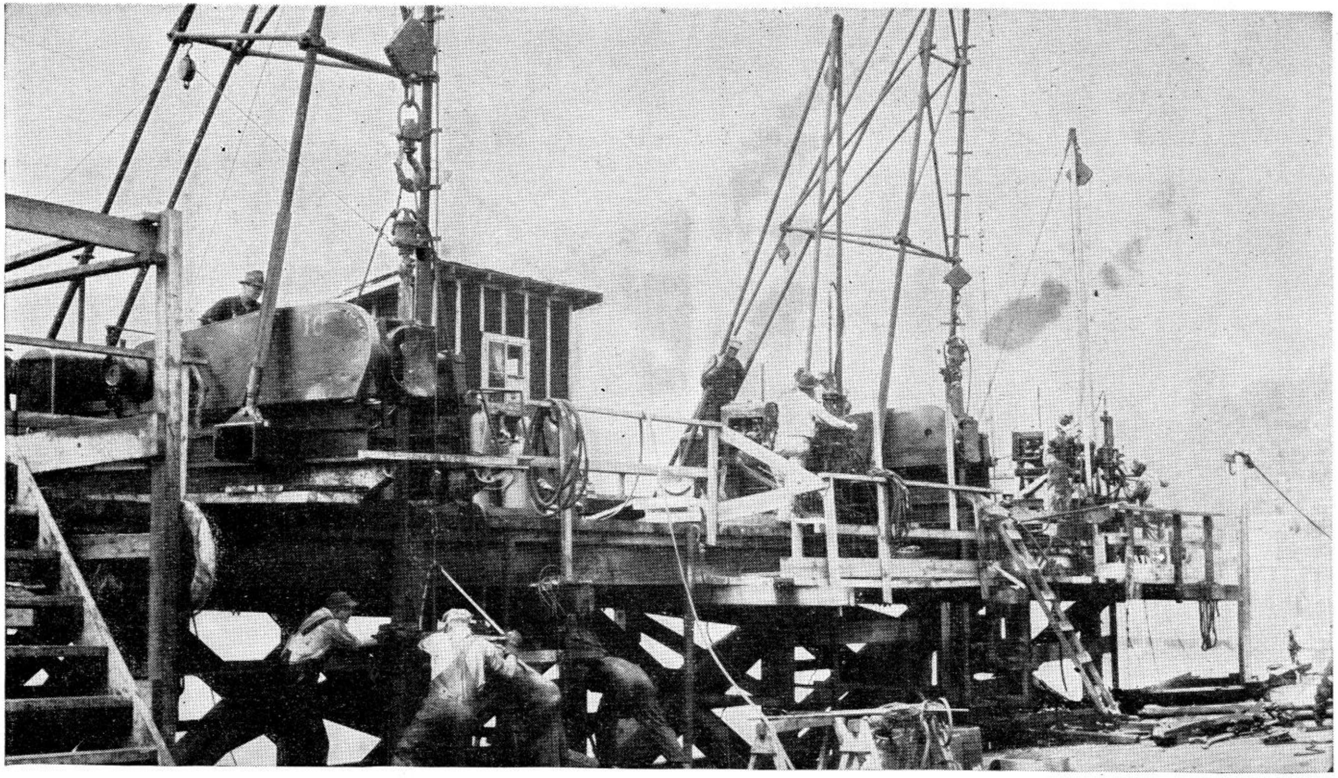
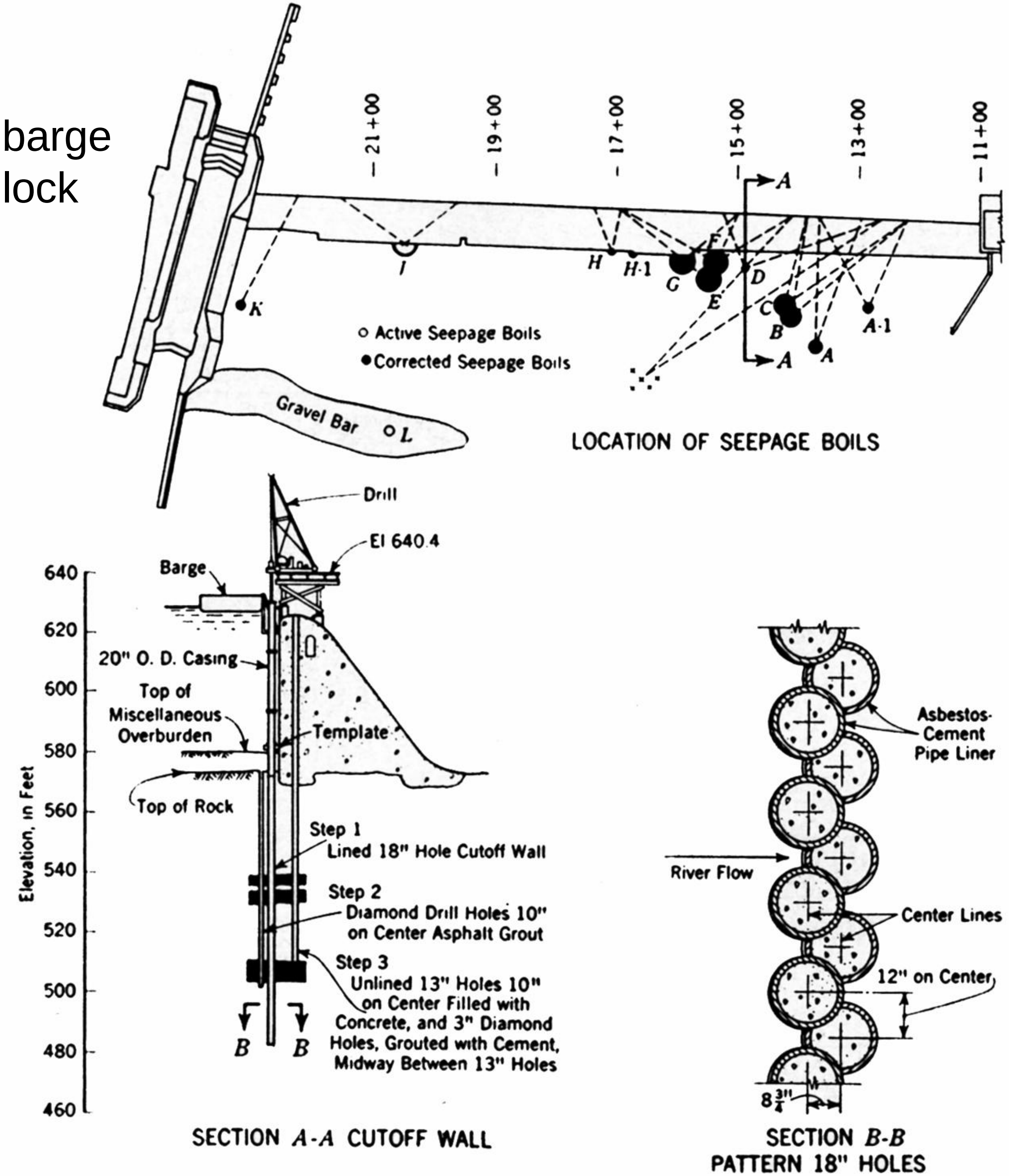


Fig. 1. Drills operating from a work bridge to make impervious concrete cutoff wall at Hales Bar Dam.

Stopping a River Under a Dam

- In 1941 the TVA began drilling 750 18-inch diameter Calyx holes, removing the rock cores, and backfilling this cutoff trench with concrete to a maximum depth of 163 feet, extending 25 to 103 feet below the river bed.

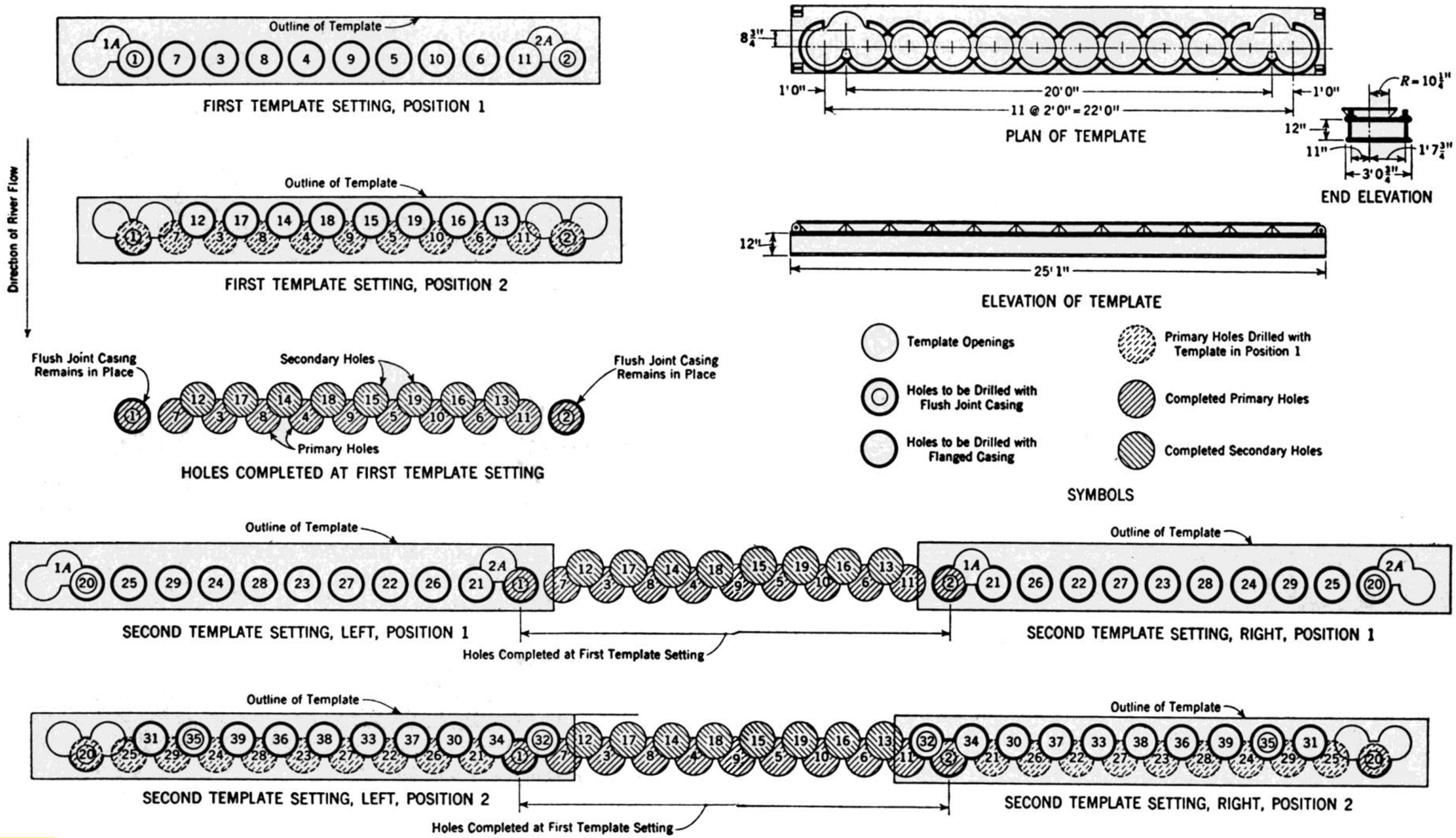
Cutoff Walls



- The TVA developed a three step process for installing a redundant series of **deep cutoff walls**, shown at left:
- 1) the main staggered 18" diameter cut off wall (plan lower right);
- 2) Diamond drill holes on 10" centers filled with asphalt; and
- 3) 13" diameter holes drilled on 10" centers filled with concrete, along with 3" diameter grouted holes between the 13" holes

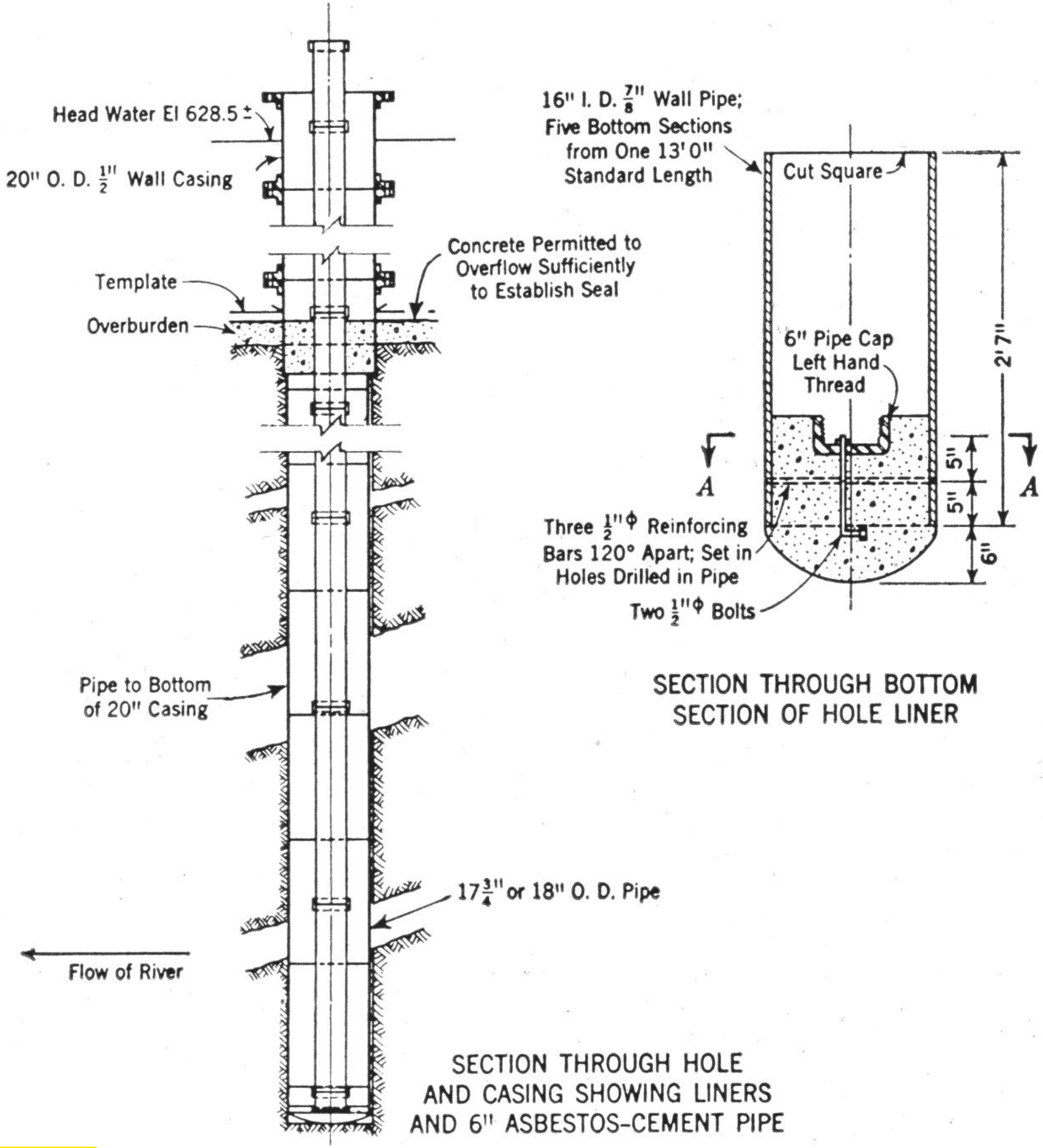
Drilling Template for tandem 18"cutoff wall

- The cutoff walls were constructed between 1940-44, the largest utilizing this 18-inch diameter drilling template and two overlapping lines of lined holes, filled with concrete
- Diamond drill holes upstream and downstream of this main cutoff wall were also grouted, using asphalt and cement grout

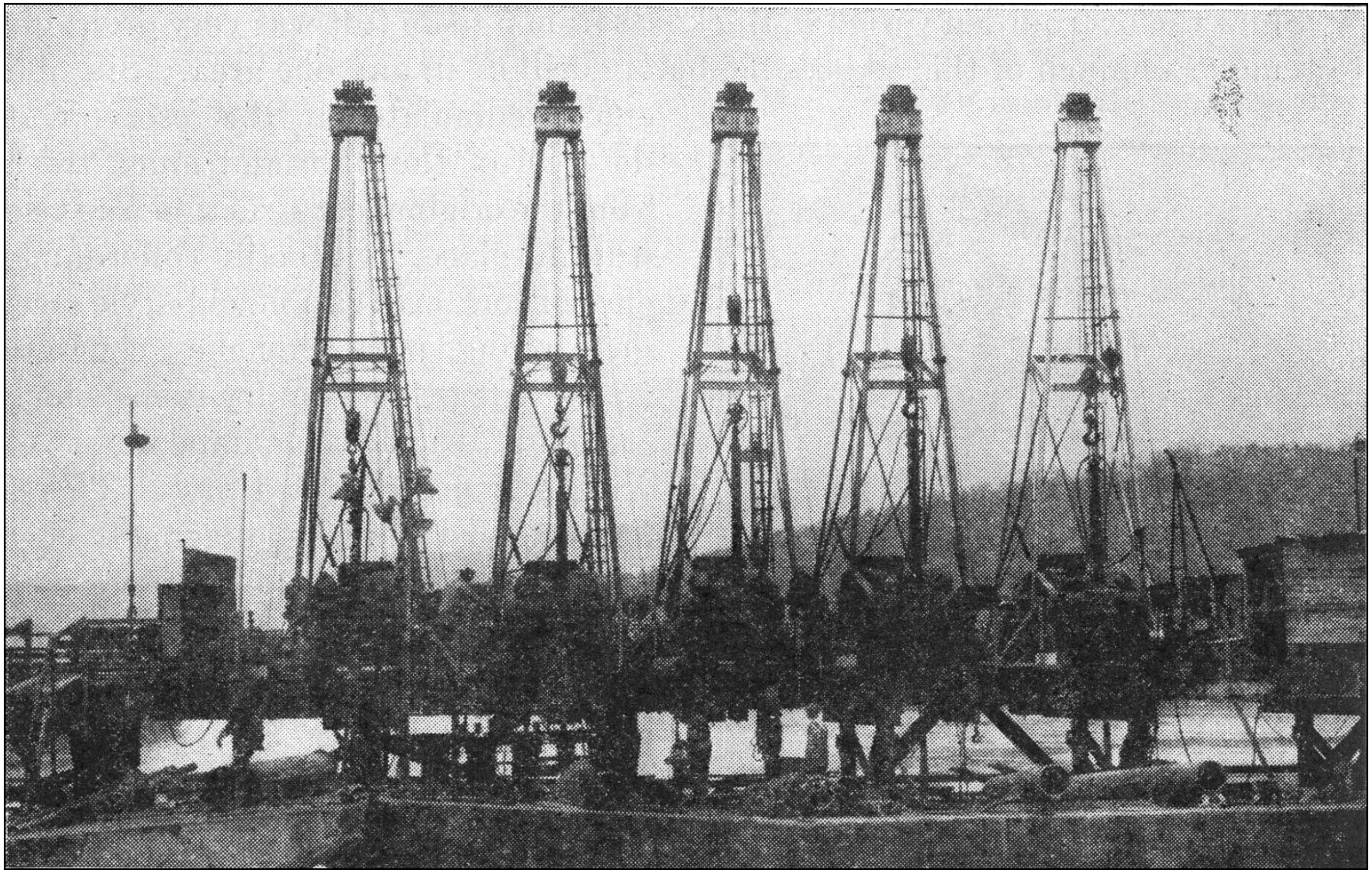


- **The 18-inch drilling template (upper right) was re-set to stagger adjacent holes to create the curtain seepage cutoff wall beneath the dam. Note drilling sequence, shown by numerals over each hole.**

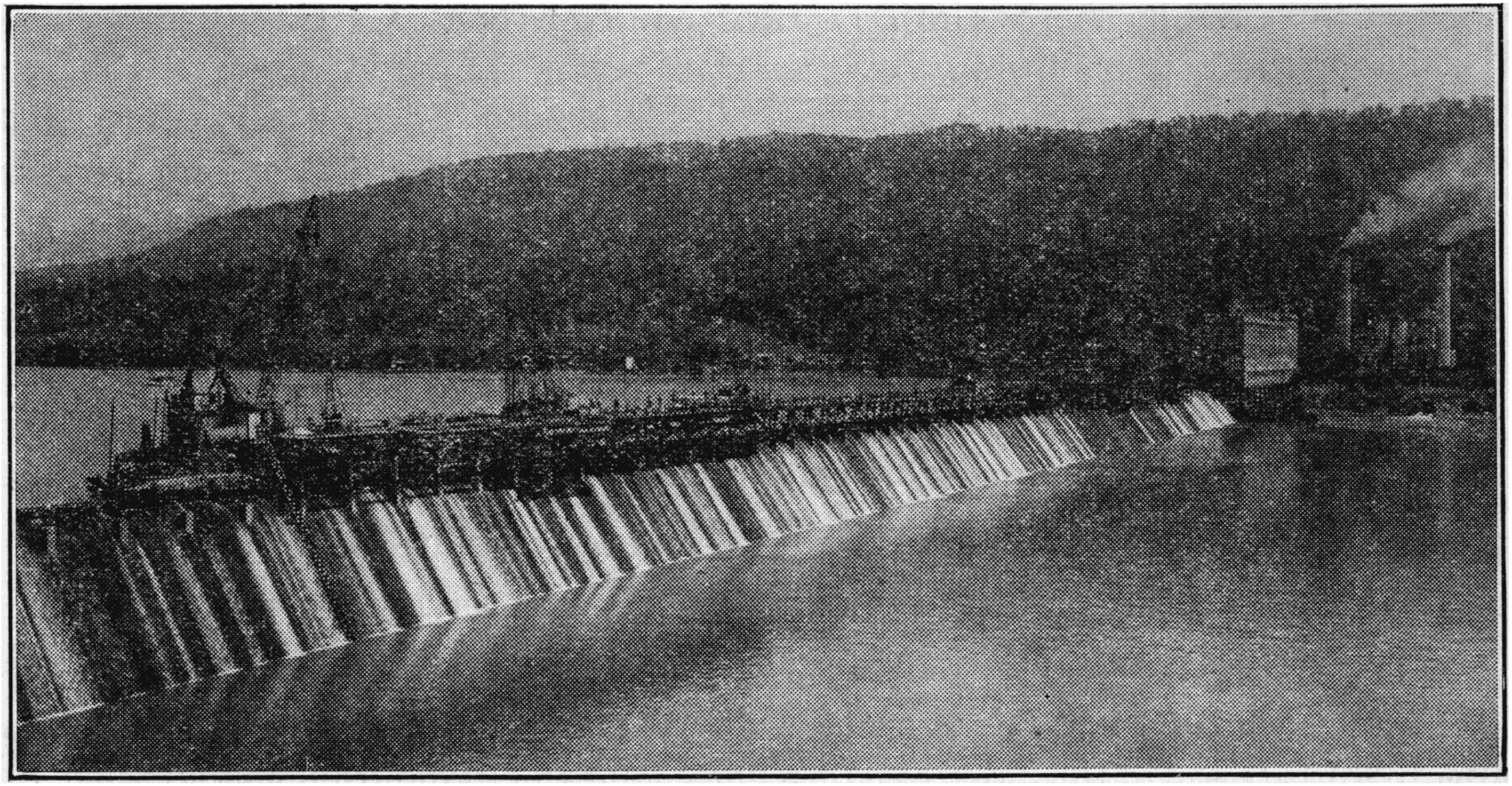
Setting new standards for cutoff walls



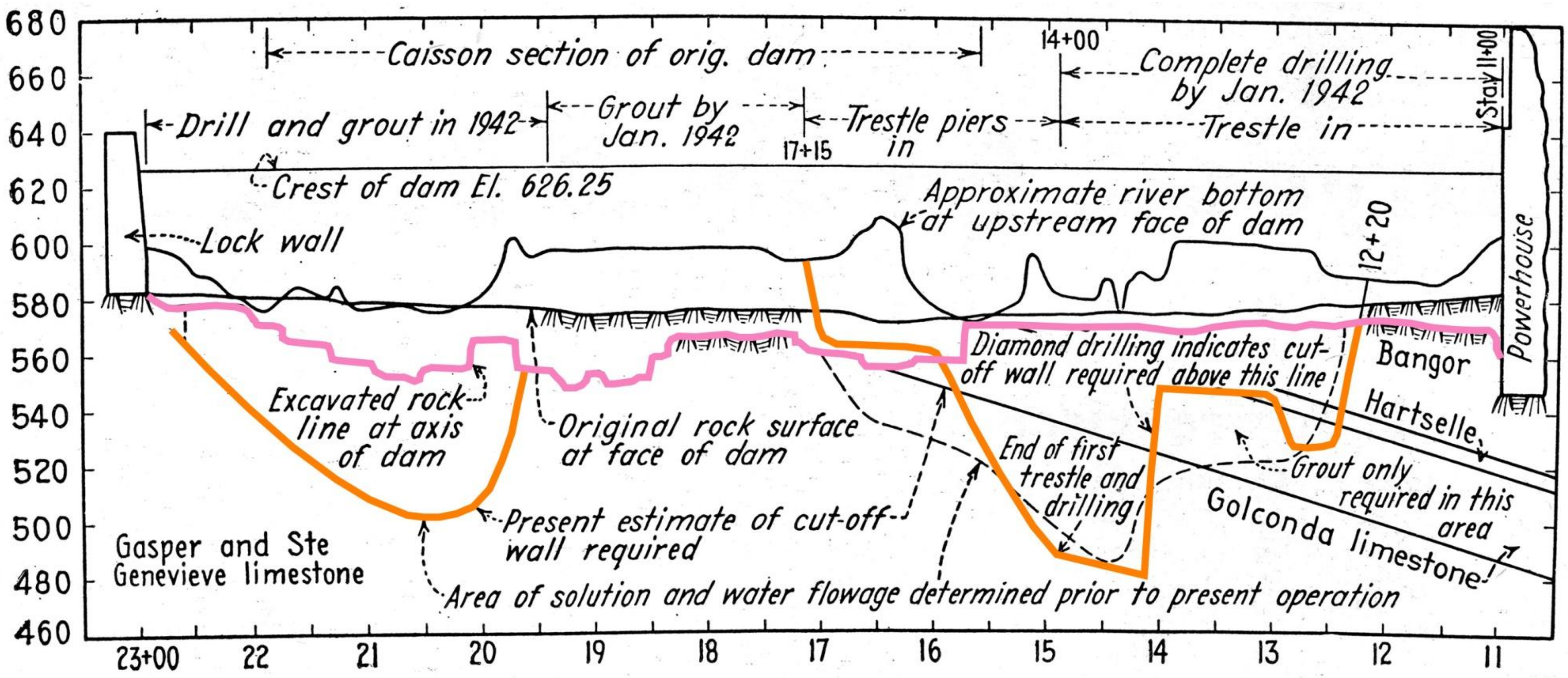
- The asbestos-cement casings used at hales Bar in the 1940s set new standards for the installation of deep cutoff walls for dams in karst; which were imitated for years thereafter



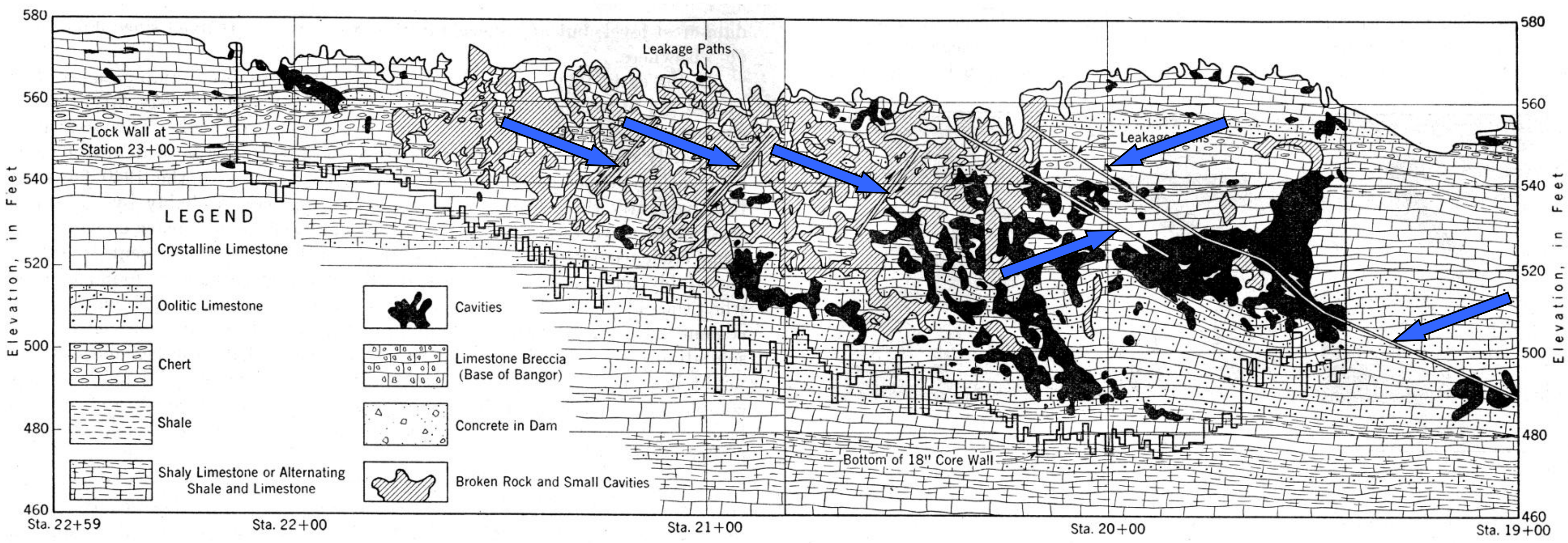
- **The contractor operated five 48-inch diameter Calyx drill rigs simultaneously. These were capable of drilling 13, 18, 24, 36 and 48 inch diameter core holes. Cores were usually recovered in 12 foot long sections (taking about 30 minutes to drill each section). The 18-inch cutoff holes were drilled 24 inches on center.**
- **After the cores were removed a current meter was inserted into each hole to record the underflow velocities, which were as high as 4.5 ft/sec. This was factored into the grout mix for each depth interval**



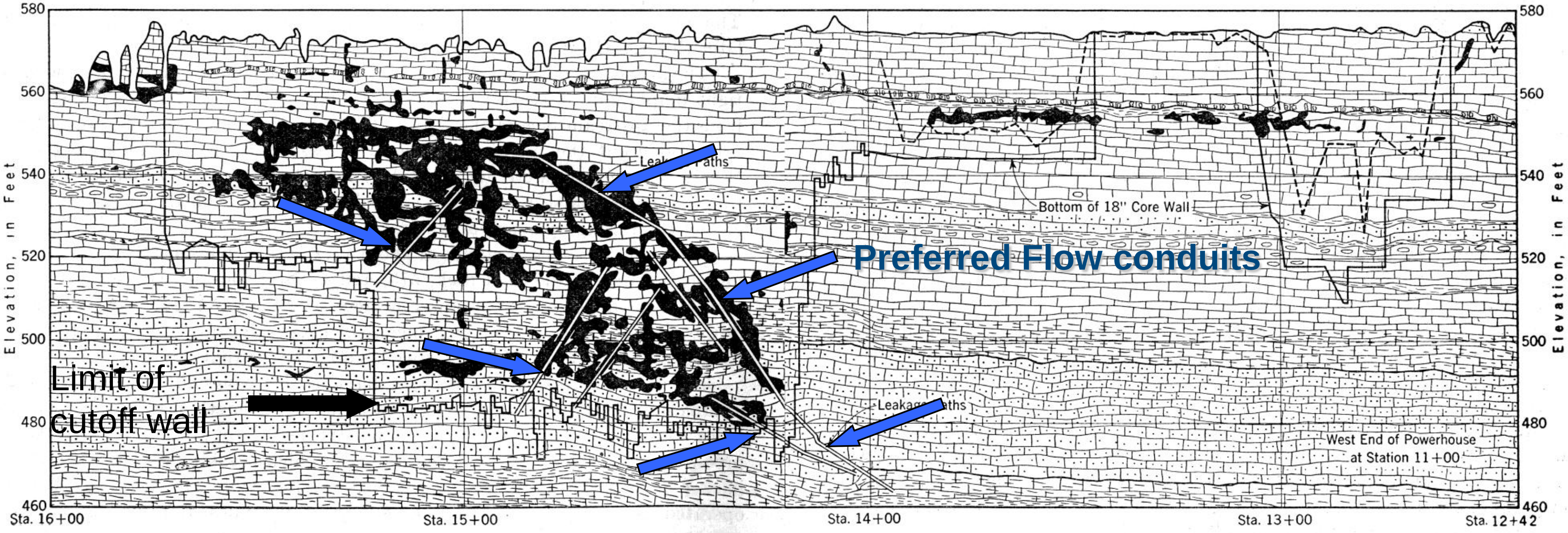
- A temporary timber work bridge was constructed over the concrete spillway section to support the contractor’s drill rigs and grouting crews during construction of the deep cutoff wall, between 1941-45. New tainter gate spillways were also added.



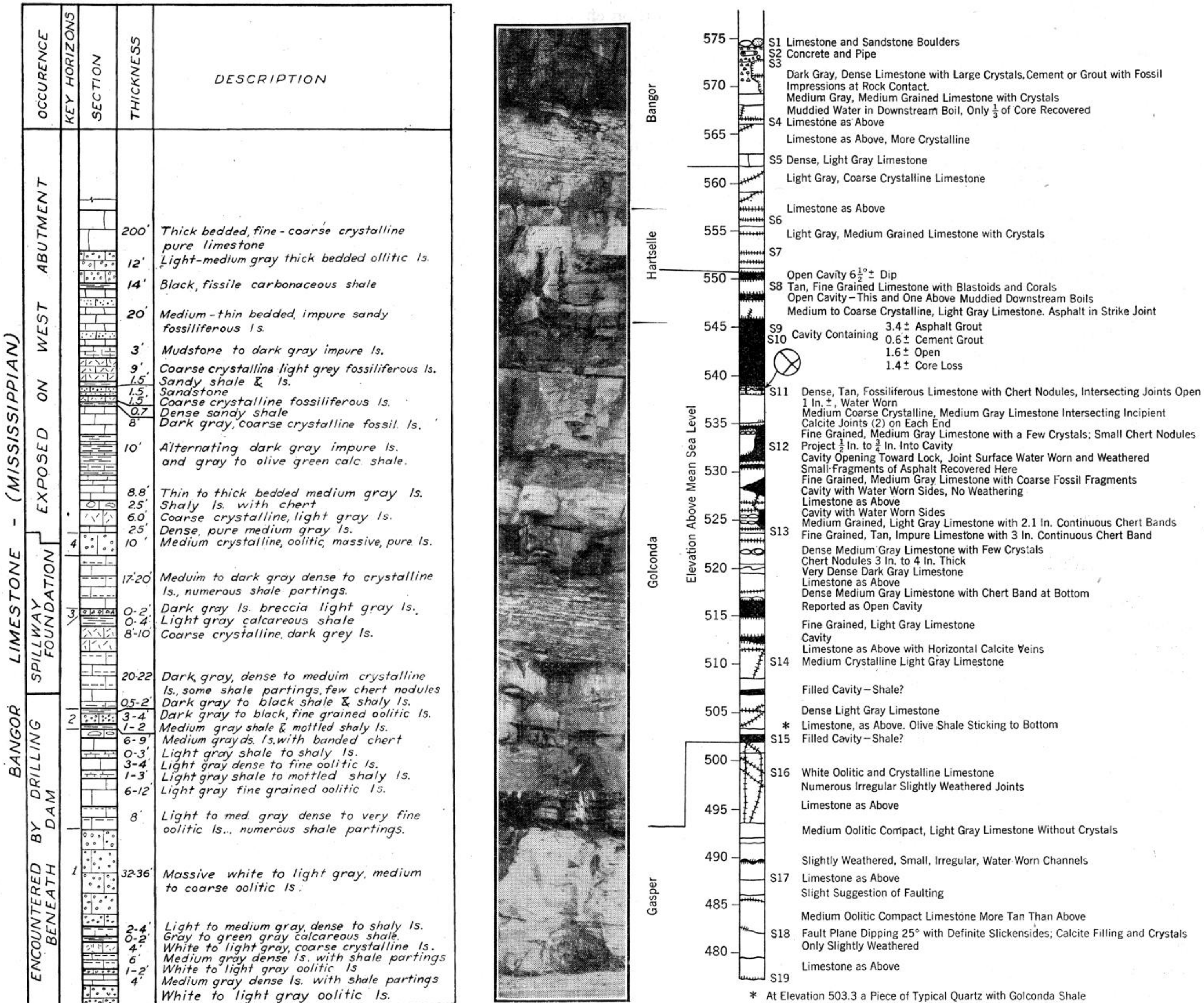
- **Profile of cutoff wall systems constructed beneath Hales Bar Dam in the cavernous Bangor Limestone**
- **Note variation between rock surface at upstream heel and toe of the gravity dam**
- **Note inclination of the most porous zones, along a series of low angles faults, parallel to the strike of the strata and the river course**



- The principal leakage paths (blue arrows) beneath the dam were discerned through logging of cores, current meter measurements, and mapping of sand boils in the channel bed below the dam.
- Note the extensive interconnected system of cavities, and the linear nature of these flow conduits.
- Note bottom of the 18” core wall, annotated above



- **Another area of filled cavities and severe underseepage encountered beneath Hales Bar Dam, looking upstream.**
- **Note the linear nature of the preferred seepage conduits, cutting across bedding.**
- **The limits of the concrete cutoff wall are shown by the solid black line.**

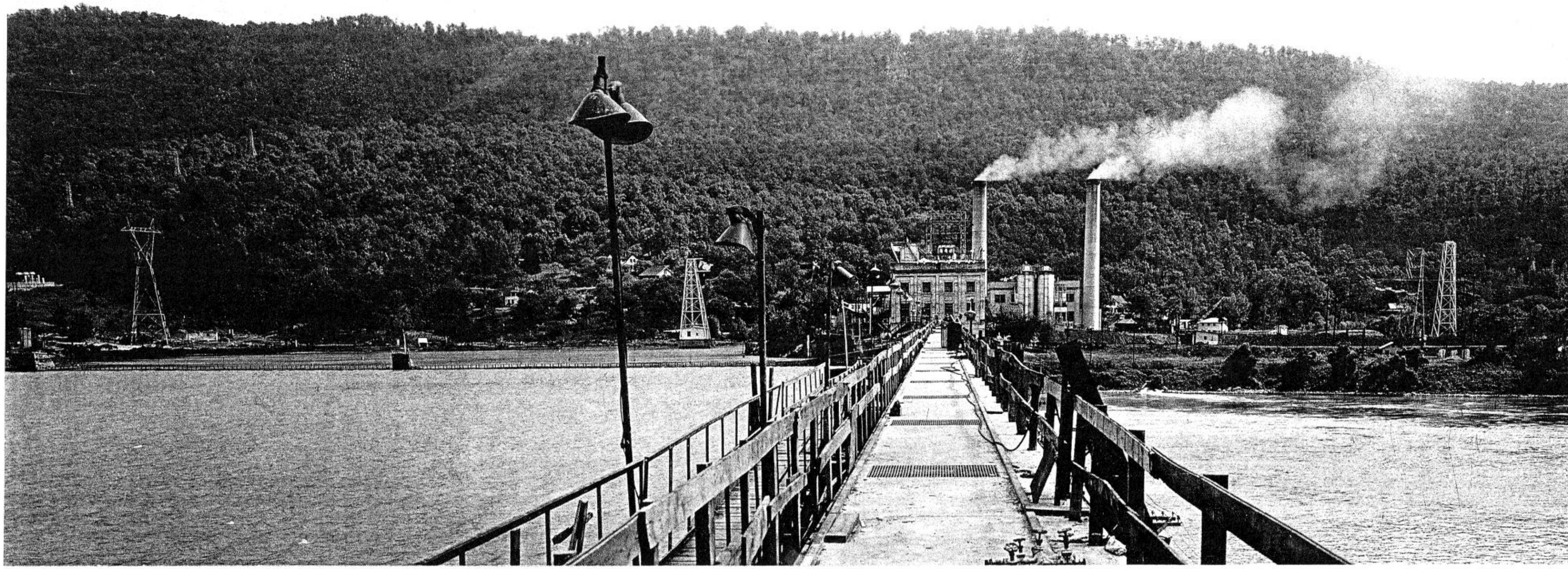


(a) COLUMNAR SECTION IN LOOKOUT MOUNTAIN SYNCLINE

(b) LOG OF TYPICAL DRILL HOLE, HALES BAR DAM

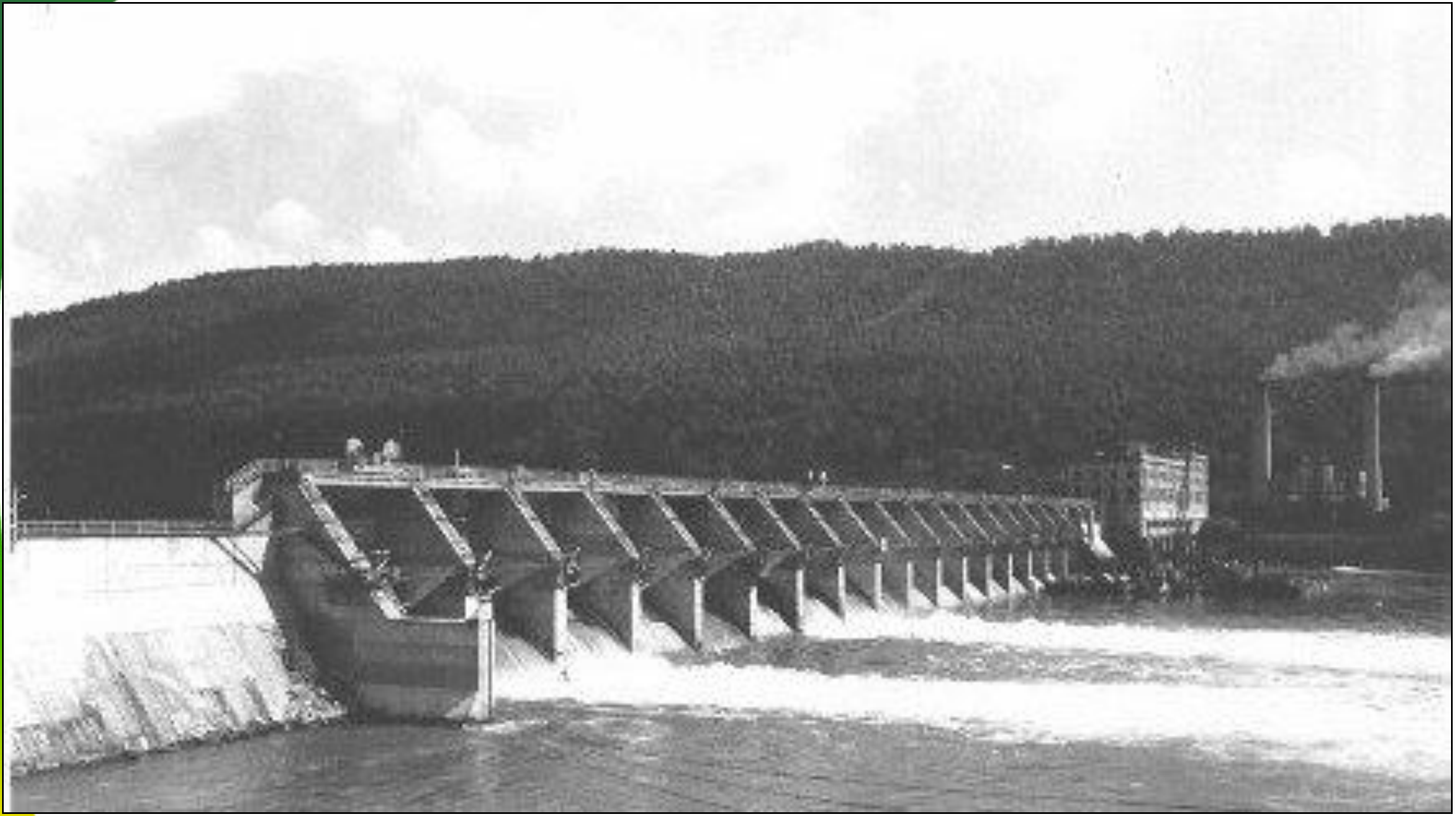
- The geologic assessments at Hales Bar Dam were among the most detailed ever made
- Discrete horizons containing cavities were identified, shown at left in black

- Detailed geologic assessments are crucial to understanding problems, but may not, in of themselves, solve a difficult seepage problem.

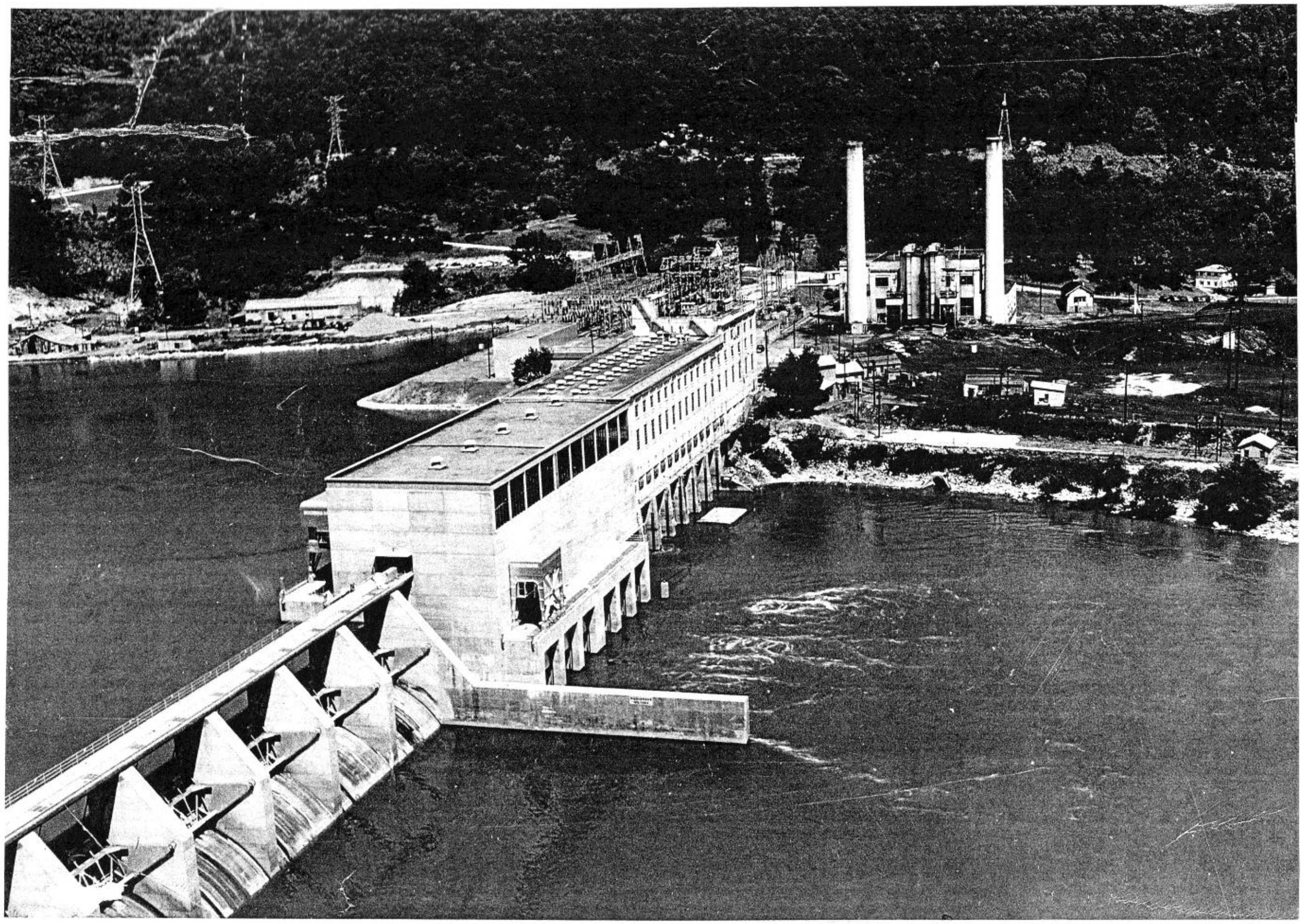


Hale's Bar DAM. During Spillway Construction, showing completed downstream portion of the deck. Looking East along operating Deck.
T. V. A. A. H. Weber, E. O. Romska, E. E. Neukom & F. L. Gutherie 9-29-1947

- **During a 1947-48 retrofit Hales Bar Dam was reconfigured with radial gates to provide increased flood storage and enhance pressure head, which allowed for expansion of the hydropower plant a few years later.**

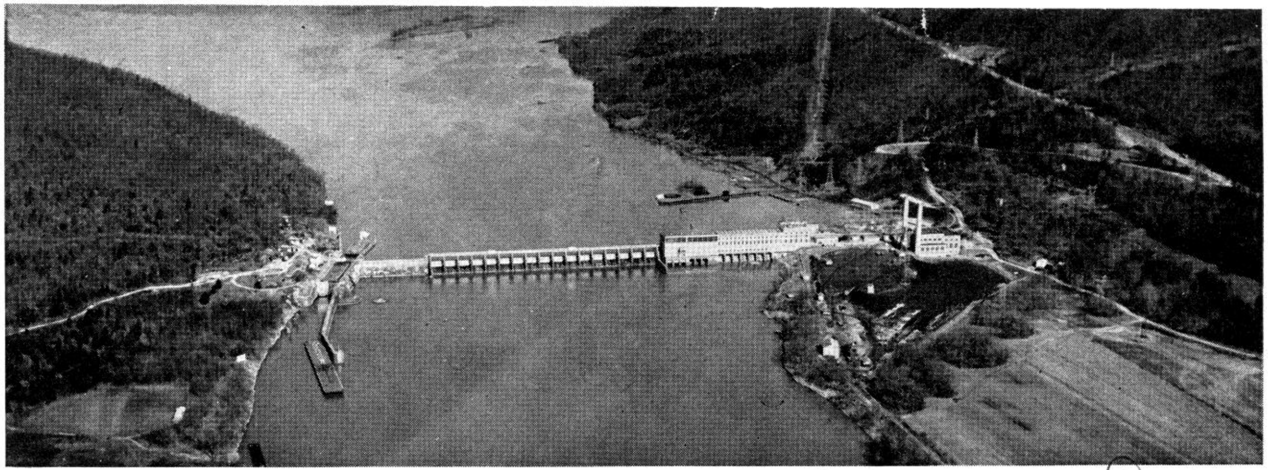


- **Hales Bar Dam in its final configuration after 1949, with a series of 20 tainter gates across the central overflow weir. The aggregate spillway capacity was 224,000 cfs.**



HALE'S BAR STEAM PLANT at HALE'S BAR LOCK & DAM on the TENNESSEE RIVER.
T. V. A. Retired the little Steam Plant 10-9-1963

- **In 1951-52 the hydro plant was expanded another 200 feet into the channel, after installing a temporary cofferdam. This was the final configuration for the project.**



A half-century of repairs is just water under the dam, so . . .

Dams

TVA Gives Up on Hales Bar Dam

Leaky old Hales Bar Dam, after taking on a 50-year parade of civil engineers, and beating them everytime, finally will bow to the Tennessee River it could never quite hold back.

The Tennessee Valley Authority has announced it will abandon Hales Bar and replace it with a new lock and dam downstream, because recent engineering studies show "that improvements at Hales Bar would be more extensive than previously indicated and their success in completely sealing and stabilizing the dam could not be assured."

TVA became the not-so-proud owner of this troublesome structure in 1939, when it acquired the assets of the Tennessee Electric Power Co.

Like every other person or organiza- 7, 1907 issue, said: "Apparently a great miscalculation was made for at this writing . . . nothing has been done on the dam or powerhouse . . . I do not believe it possible to finish this work in under two years. . . ."

In a 1909 ENGINEERING RECORD, engineers still didn't sound truly aware of how serious the foundation problem really was. "At Hales Bar . . . the river bed is a limestone formation with strata dipping slightly and covered with 8 to 10 ft of sand and gravel which fills an ancient channel under the present river bed."

The dam hadn't even been started but, "excavation on the powerhouse developed a rush of water of 15,000 gpm at a level of 33 ft below the surface of A careful examination is made by means of drill holes 8 to 12 ft deep." If bad rock was discovered, grout pipes were installed and grout pumped in after the caissons were founded and filled with concrete.

Soon after Hales Bar went into service, leakage was detected under the dam. Over the years various methods for plugging the leaks were tried. But not until 1925 did engineers succeed, at least temporarily, in stemming the flow, with hot asphalt pumped down holes drilled through the dam.

By 1941, however, the new owner, TVA, was logging a cool 1,700 cfs under Hales Bar Dam, and its engineers thought they had a way to stop the water.

- **In April 1963 the TVA announced it was abandoning Hales Bar Dam, due to increasing leakage. In addition, the old locks were less than half the size of the 110 x 600 ft locks used elsewhere along the upper Tennessee River. The powerhouse remains and the old locks have been converted to a coal barge terminal.**

Limitations of conventional grouting in karst terrain

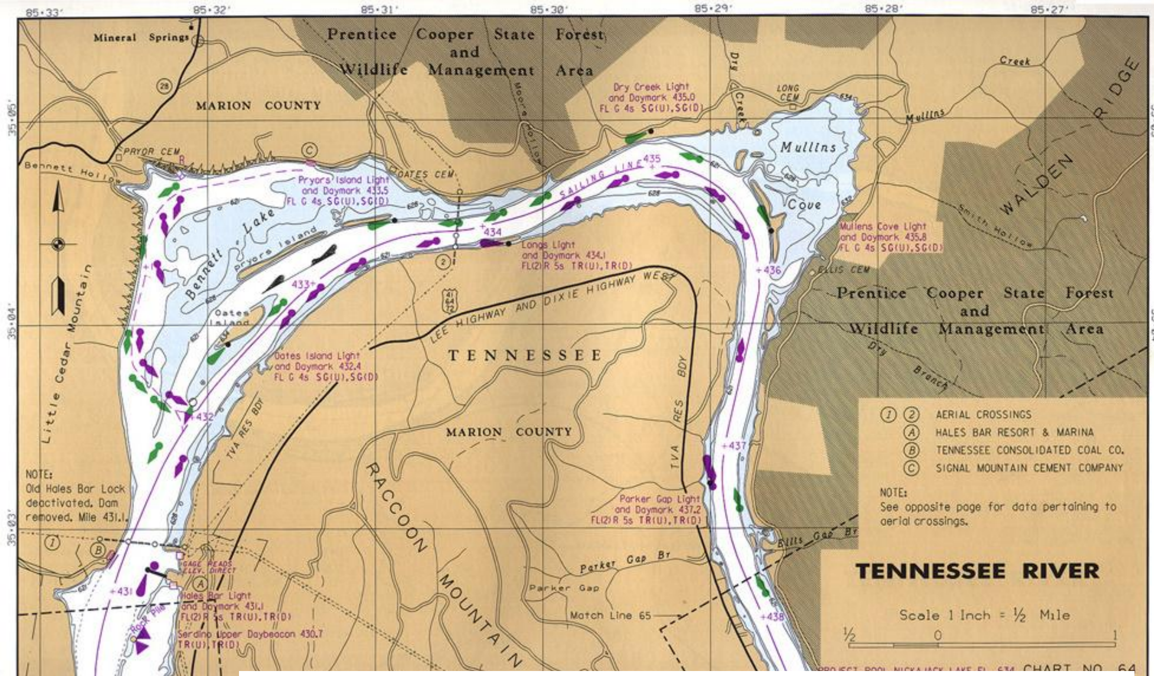
- Cavities in old karst terrain are usually partially filled with residual clay and rock detritus
- The cavity chambers are intricately interconnected by joints, shears, and faults enlarged by solutioning
- Grouting through vertical holes can only penetrate finite distances from the drillholes, commonly 5 to 25 feet. This distance is a function of grout slump, mixing with running water under pressure head, and tortuosity of the grout flow paths
- Today's computerized drilling technology utilizing inclined injection holes can actually handle many of these situations, but at significant cost

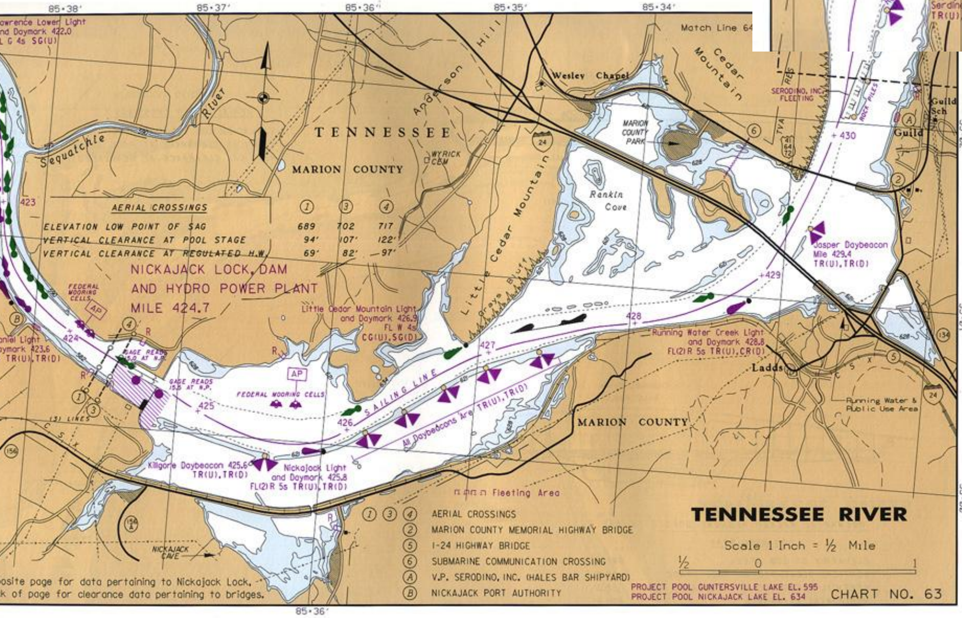
Why grout curtains in karst terrain typically degrade with time

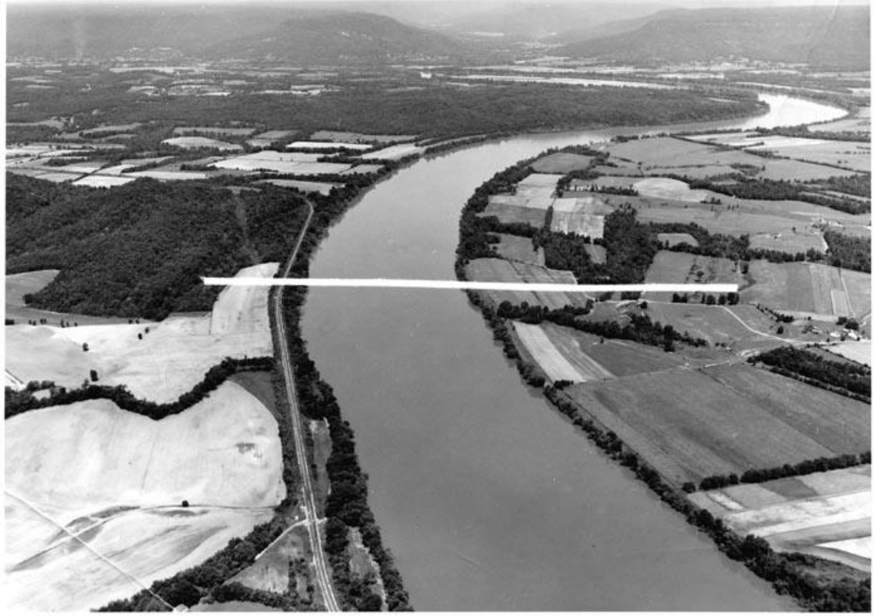
- Whenever the grout curtain is injected into clay-filled discontinuities and cavities under active pressure head (full reservoir conditions); the grout curtain initially "holds" back the seepage
- In doing so, hydrostatic pressures up-gradient of the curtain are increased to levels never realized previously
- This increased pressure eventually results in "clay plugs" being expunged from some of the cavities adjacent to where the grout penetrated, opening up new cavities that gradually enlarge themselves as effective underflow conduits

Nickajack dam site

- **In 1963 TVA selected an alternative dam site 6.4 miles downstream of Hales Bar**







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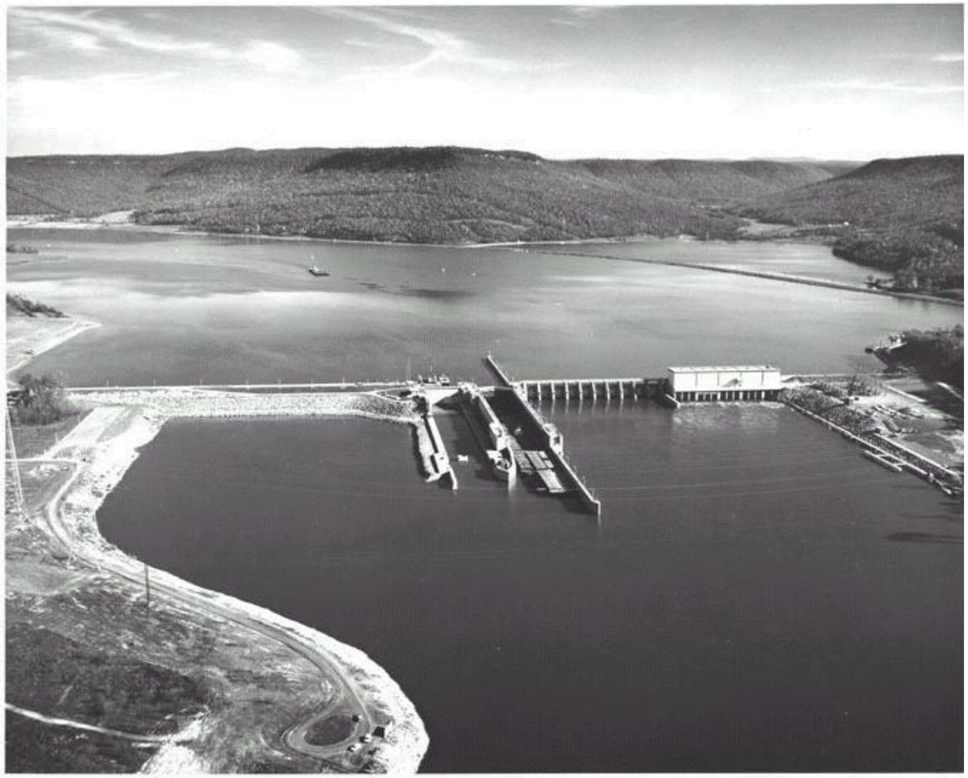
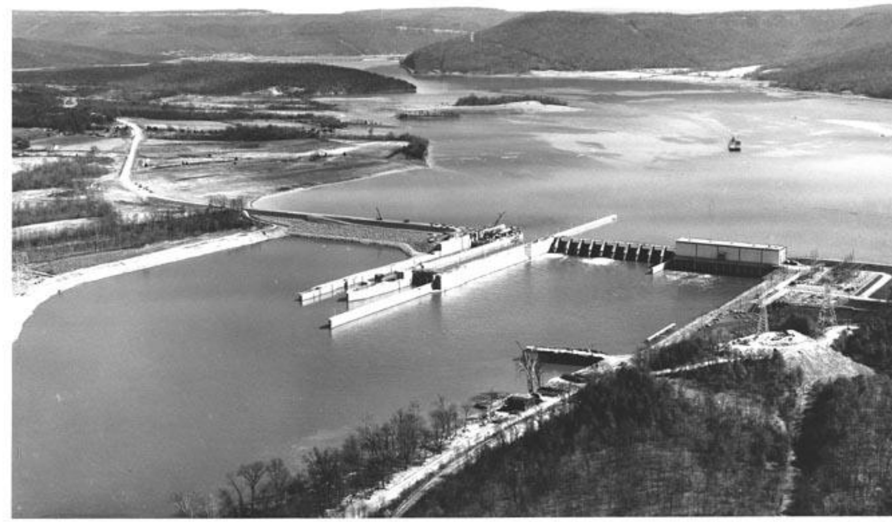
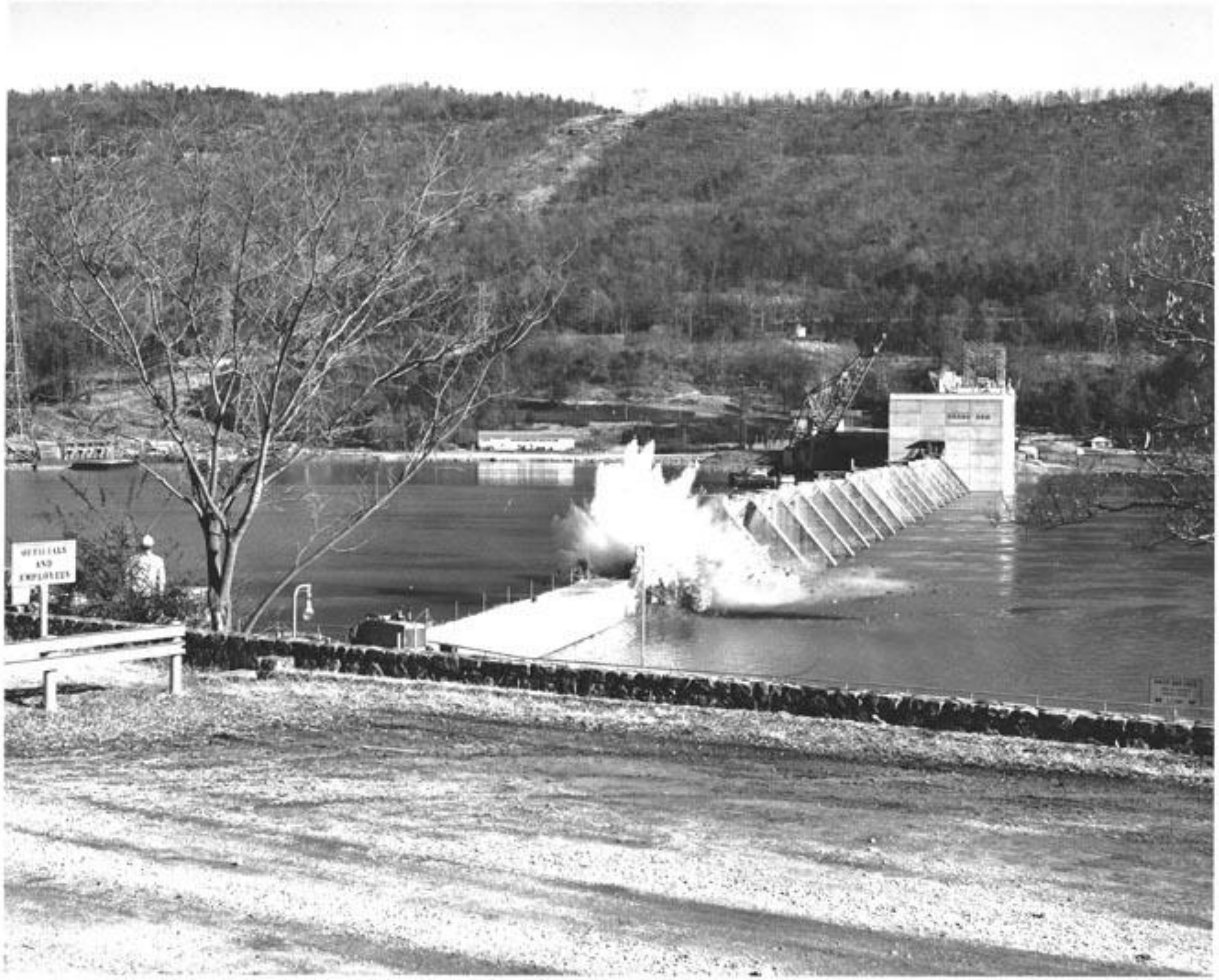




Nickajack Dam and Lock

- In 1964 a diversion channel was dredged around the new dam site to maintain riverine navigation. It began impounding water in December 1967.
- The new dam has parallel navigation locks, a 10-bay spillway, and 4-unit powerhouse, generating 97,200 kw
- When completed in 1968, it was 22^{nd} dam built by the TVA



- **Demolition of the 1000-ft wide spillway overflow section of the old Hales Bar Dam was carried out in 1967-68, as seen here from the right bank. The hydro powerhouse was gutted of all equipment, but left in-place.**

Thermal Power Plant dismantled

- **On June 19, 1965 demolition of the steam generating electric power plant began, razing the two 200-ft high smoke stacks.**

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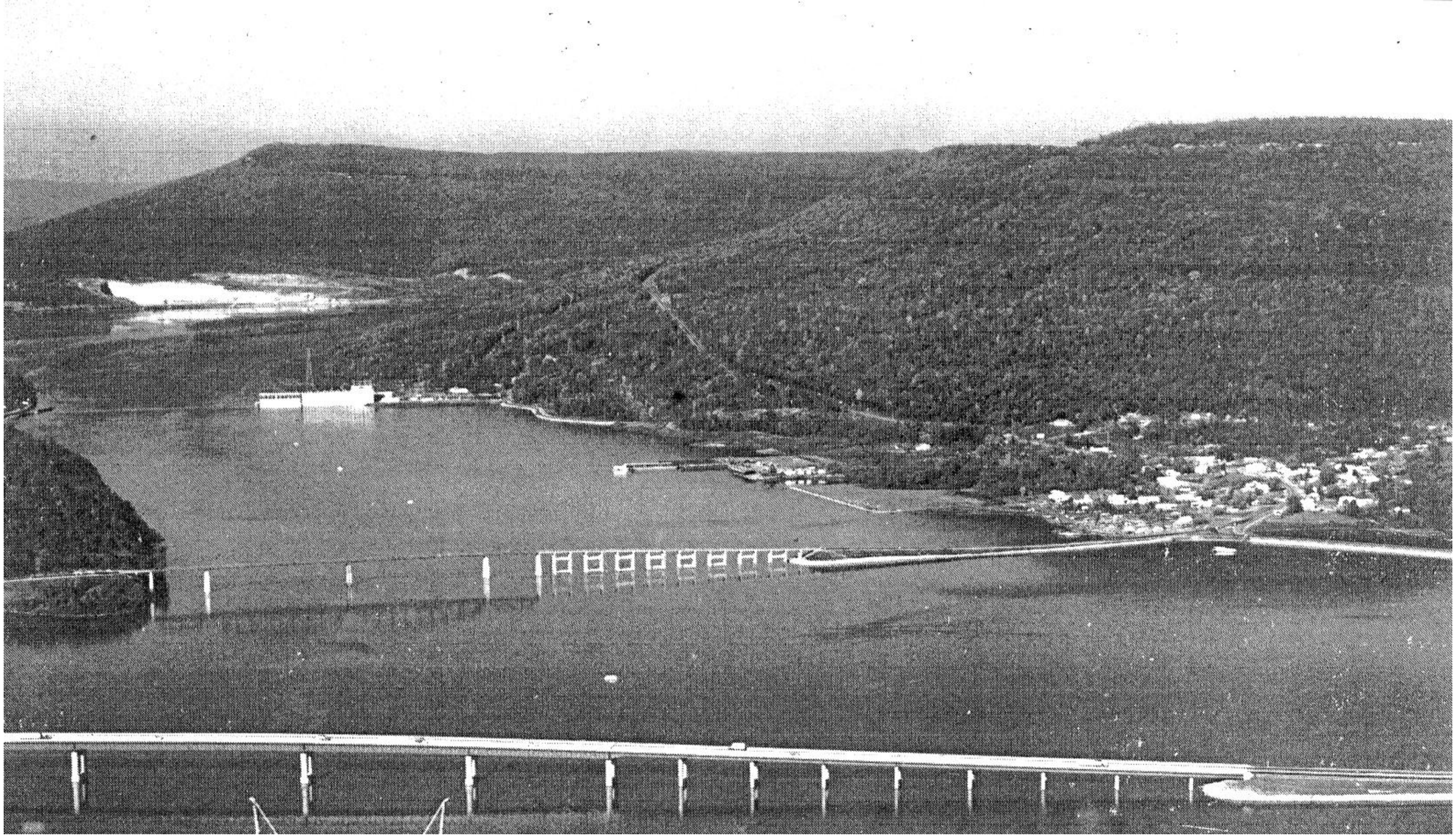
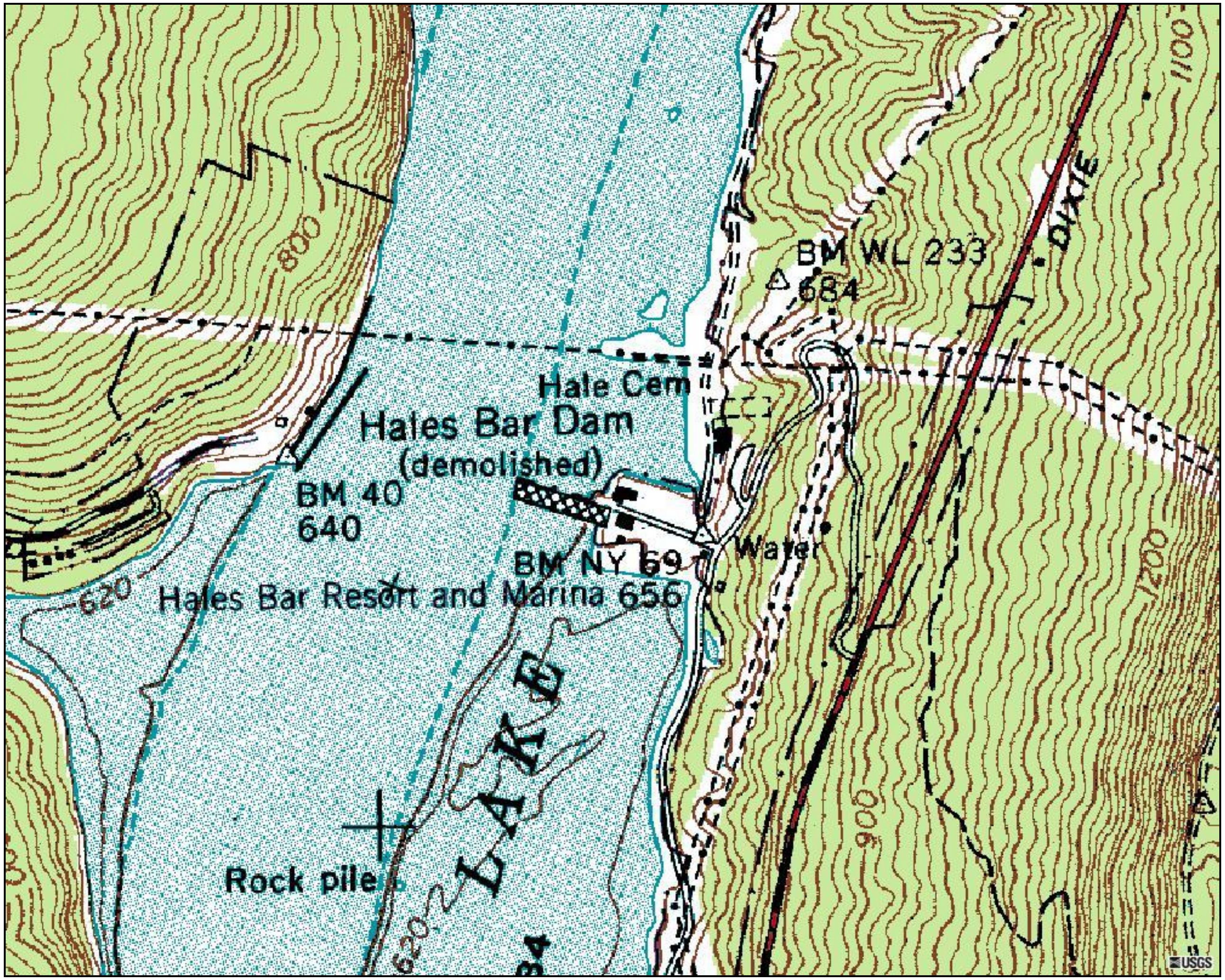
Hales Bar Marina today

- The shells of the old hydroelectric powerhouses remain on the river’s left bank, within Nickajack Reservoir (seen at upper left).
- The buildings are used for boat storage, as shown at lower left.



- **Today Interstate 24 passes within easy viewing distance of the old dam, and the powerhouse is presently used for boat storage and as a marina.**



- **Hales Bar Dam was the first dam owned by a federal agency (TVA) to be removed because of engineering problems.**
- **Today its remnants lie within Nickajack Lake, along the Tennessee River, as shown in this 1988 USGS map.**

This lecture will be posted at

www.mst.edu/~rogersda/dams

in .pdf format for easy downloading and use by others.

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