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HYDRAULIC LABORATORY REPORT NO. 31

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HYDRAULIC MODEL TESTING OF STRUCTURES

by

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Hydraulic model experiments were begun by the Bureau of Reclamation in 1930 in the laboratory of the Colorado Agricultural Experiment Station at Fort Collins, Colorado. The unprecedented magnitude of the various structures being designed for the Boulder Dam was undoubtedly responsible for the introduction of this innovation into Bureau design practice. The subsequent growth of the laboratory plant and the scope of the investigations as well as the increase in personnel has been indicative of the success with which the models of the last six years have supplied the information needed by the design department.

In the latter part of 1930 a staff of twelve, including engineers, carpenters, and assistants, was assigned to the small laboratory at Fort Collins with instructions to build a model of one of the two shaft spillways originally proposed for the Boulder Dam. Tests on this model showed conclusively that the shaft spillway was not suited to the anticipated operating conditions. As a result, the side-channel spillway was proposed, and models of various modifications of this type were tested intermittently during a period of two years. The magnitude of even the auxiliary features of the Boulder Dam is difficult to comprehend. Each of the two side-channel spillways is designed to receive and to discharge, after a drop of 500 feet, a maximum flow of 200,000 second-feet without permitting destructive erosion.

The experience gained during the foregoing tests demonstrated clearly that the hydraulic model provided practically the only means of ascertaining and eliminating such undesirable conditions as spiral flow in circular tunnels or the choking of shaft spillways. In recognition of the value of these models for supplementing the work of the design section, the Bureau of Reclamation now maintains three hydraulic laboratories with a combined staff of about fifty men. These laboratories are situated in the vicinity of Denver and permit close contact with the design section.

PROBLEMS OF THE LABORATORY

Since 1930 approximately eighty models have been constructed and tested in the three hydraulic laboratories. Each of these has resulted in either (1) an improvement in flow conditions through minor revisions of the original design, (2) an improvement in flow conditions combined with the development of a more economical structure, or (3) an improvement in flow conditions necessitating a more expensive design. Model studies do not always result in a more economical design. In a number of cases, however, the saving effected has many times offset the cost of the experiments. Seldom has the original design of a structure been found so nearly perfect that desirable revisions have not been suggested by the model studies.

The structures most frequently tested in the hydraulic laboratory include spillways, stilling pools, outlet tunnels with control valves and Venturi meters, intake structures, needle valves, and hydraulic turbines.

SPILLWAYS AND STILLING POOLS

Of the types of models listed in the foregoing paragraph, spillways and stilling pools have been the most frequent. This is evident from the tabulation shown on page 4 in which are listed the major hydraulic structures that have been tested since 1930. Spillways fall naturally into five general classifications - the "glory-hole" or shaft-type (photograph 1, page 5), the side-channel type (photograph 2), the overflow type (photographs 3 and 4), the open-chute type (photographs 6, 7, and 8), and the enclosed tunnel chute (photograph 5). Of these the first two seldom require stilling pools since they are usually employed in conjunction with large concrete or masonry dams founded on bedrock where no erosion hazard is involved in permitting the water from the spillway to impinge upon the stream bed directly below the dam.

The overflow type of spillway is suited to a wide range of conditions. It may be used either with a high dam founded on bedrock and provided with a natural stilling pool such as is contemplated for the Grand Coulee Dam on the Columbia River, or it may be adapted to the smaller concrete or masonry structure such as the Imperial Dam on the Colorado River, which rests on a sand and gravel foundation. In the latter case, a well-considered artificial stilling pool is required.

The open-chute spillway is frequently used in conjunction with earth dams. It follows the general profile of the downstream face of the dam and terminates in an artificial stilling pool. The typical pool comprises a horizontal concrete apron, on the downstream end of which is constructed a concrete sill or a set of baffles. The apron may rest directly upon sand or gravel, and since its function is to protect that material from erosion, its proper construction is an important requisite to the safety of the dam. A stilling pool is a basin in which the energy of the falling water is violently dissipated without damage to the river bed; it reduces the turbulence and wave action downstream from the spillway and is, therefore, particularly essential to earth dams.

The enclosed tunnel-chute type of spillway is seldom used. A gate section is usually required at the mouth of the tunnel, and the flow conditions produced by the presence of this gate section are seldom satisfactory.

Analogous to the manner in which a newly designed machine is thoroughly inspected for defects and imperfections at the factory is the procedure by means of which models of hydraulic structures are built and tested in the laboratory before the design is finally adopted and committed to construction. The models reveal undesirable features of the design and indicate the proper means for their correction. Due to the frequency with which spillways have been tested in the laboratory, a rather definite and efficient routine of inspection has been developed. This is conveniently separated into the following six phases:

1. Inspection of the flow in the approach to the gate section. If the approach channel is shallow, or if the entrance to the channel is abrupt, either condition will usually effect a reduction in the capacity of the spillway.

2. Inspection of the flow, and measurement of the head loss through the gate section. A reduction in the loss of head through the gate section will usually result in an increase in the capacity of the spillway. In the majority of cases such a result is to be desired. Slight alterations in the approach, or changes in the piers, will frequently effect a reduction of the crest losses. The character of the flow through this section is also largely responsible for the distribution of flow across the face of the spillway, in the chute, or in the stilling basin.

3. Measurement of pressures on the face of the spillway. For overfall dams it is important that no appreciable sub-atmospheric pressures shall exist on the downstream face. Pressures on these surfaces are measured by piezometers in the model which are simply short tubes inserted flush and normal to the spillway face. Rubber hoses are used to connect each of these tubes to manometers. Where sub-atmospheric pressures are observed, they can usually be eliminated by minor alterations in the shape of the face.

4. Inspection of flow characteristics in open and closed chutes. Most of the difficulties encountered with chutes arise from some form of direction change imposed upon the flow. In some chutes a laterally contracted or "corset-shaped" section is attempted for structural reasons. The spillway in photograph 6 is illustrative of this type. Other forms of open chutes involve horizontal curves which must be superelevated as are the curves on highways and railroads. Such a spillway is shown in photograph 8. Models of chutes have revealed and made possible the elimination of many unexpected

and undesirable conditions such as overtopping of sidewalls, unbalanced combinations of flow, or high standing waves.

5. Investigation of the stilling pool performance. In addition to being the most spectacular part of the spillway, the stilling pool is probably the most important. The failure of the stilling pool to operate properly under all conditions may, in many cases, endanger the entire project, including the dam. The stilling pool must be as efficient in dissipating energy as is the spillway-gate section in conserving energy. Of the many forms of stilling devices in operation, the most successful are those that assist rather than impede the formation of the hydraulic jump. Sills and sloping aprons serve to stabilize the jump within the paved limits of the pool. Because of its importance, the testing of stilling-pool designs is accorded the most exacting consideration and occupies a large proportion of the time devoted to spillway studies.

6. Calibrations. Each spillway is calibrated to determine its capacity at the maximum designed and at intermediate heads. Frequently, unforeseen losses reduce the capacity of the spillway below the value specified in the design. Under such circumstances minor revisions can frequently be made which will suffice to increase the spillway capacity to the required amount.

When a model has been successfully subjected to each of these six phases of testing, few uncertainties in the hydraulic design remain.

OUTLET TUNNELS WITH CONTROL VALVES AND METERS

Probably one of the most difficult tasks for the designer is the computation or prediction of flow conditions downstream from gates or bends in outlet tunnels. If there is more than one gate in the tunnel, the possible combinations of gate openings and the variations in the resulting flow conditions may be numerous. Since the tunnels are usually designed to flow partly full, lateral bends considerably complicate the flow.

Six outlet structures have thus far been tested, including those for the Boulder, Alcova, Caballo, Bull Lake, Owyhee, and Friant

Dams. Each project presented entirely different problems, and quite diverse solutions were obtained.

The most outstanding of the six outlet structures tested was that of the Boulder Dam tunnel-plug outlets. Each outlet will comprise a battery of six 72-inch needle valves which will discharge a maximum of 22,000 second-feet into a concrete-lined tunnel 50 feet in diameter. A portion of this model is shown in photograph 9. The model needle valves were made adjustable in the vertical and horizontal planes so that the setting of each valve, which would be most favorable to smooth flow at the maximum discharge in the large tunnel, could be obtained. The same setting was found satisfactory for flows less than the maximum, provided that the openings of the valves were symmetrical. To provide a check upon the effect of the scale ratio, two additional models were made on different scales. The valve settings finally determined represented a distinct improvement over those originally proposed.

The tests on the Caballo Dam and the Bull Lake Dam outlet works were similar in nature. Each involved vertical slide gates operating in tunnels which discharged into stilling pools. The two models are shown in photographs 10 and 12 on page 5. The criteria of a satisfactory solution for this type of model are (1) smooth flow in the tunnel downstream from the gates under all operating conditions, (2) effective and dependable stilling-pool characteristics, (3) assurance that the hydraulic jump will not travel upstream into the tunnel but will remain within the limits of the pool under all conditions. To obtain satisfactory flow conditions in the Bull Lake tunnel it was necessary to fix a definite gate-operating schedule that would eliminate unfavorable combinations of openings. The tests on the Caballo outlet showed that substituting a horseshoe tunnel for the originally proposed circular tunnel would materially reduce the sinuous flow. On both models a rounded "hydraulic hump" or spreader (photograph 12) was interposed between the tunnel outlet and the stilling pool. This served both to produce a jet of uniform thickness and to prevent the surface roller of the hydraulic jump from moving back into the tunnel at low discharges.

An interesting feature of the Owyhee tests on an irrigation outlet tunnel was the rectangular Venturi meter-flume (photograph 11) included in the tunnel section upstream from four vertical slide gates. This tunnel now serves to control large storage releases from the Owyhee reservoir. Water from the tunnel, which is three miles long, is delivered to the open channel of the main project canal. The model was used primarily for the calibration of the Venturi meter-flume. The curves obtained exhibited three distinct phases corresponding to the three ranges of flow, Venturi throat flowing free, throat flowing full but main entrance to tunnel partly full, and tunnel and throat flowing completely full. The result was deemed highly satisfactory, and could have been obtained in no other way except by expensive field measurements.

INTAKE TOWER

Unique among the structures which have been tested in the Reclamation laboratories was the model of one of the four Boulder Dam intake towers. This model (photograph 13) afforded a means of observing the flow through the tower under different operating conditions, and made possible the measurement of the losses at several points within the tower. The results provided an excellent check on the design computations.

VALVES AND GATES

With the exception of a series of experiments made in an attempt to improve the mechanical and hydraulic features of stoney gates, all the tests on gates and valves have been concerned with closed conduit control. An interesting study of ring-follower and cylinder-follower gates revealed important defects in previous designs and pointed the way to satisfactory revisions. Numerous needle-valve tests have been made, the outstanding of which were those for the Boulder Dam previously mentioned. A battery of four 96-inch needle valves for the Kern County outlet of the Friant Dam has also been tested. These valves discharge directly into a stilling pool at the entrance to the canal. A valve setting was evolved which completely eliminated the necessity for sills of any kind in the pool.

HYDRAULIC TURBINES

Model studies for obtaining a more efficient draft tube for the turbines of the Wheeler Dam on the Tennessee River have been made in the Denver laboratory. A stationary runner was constructed with fixed vanes which could be set at any angle to induce the whirl in the draft tube. Such tests yield only comparative results, and are chiefly valuable in providing qualitative information as to the relative value of proposed designs. It is assumed that the draft tube which gives the better results in the model will also give optimum performance in the prototype.

Draft tube experiments are now being made on a model of one of the turbines for the Grand Coulee Dam. This is a complete working model with movable runner, governor, and generator. Direct observation of the flow within the scroll case and the draft tube is made possible by the use of transparent pyralin in forming all of the outer walls. A side view of this model may be seen in photograph 14.

MISCELLANEOUS TESTS

The tests which have been cited thus far have related to hydraulic structures of considerable size. Models of minor structures and other features difficult to classify have included canal chutes with stilling pools, ejectors, roller gates, a silt scraper for the All-American canal desilting works, seepage under the Imperial Dam which will be founded on a porous foundation, silt movement in the Colorado River above the Imperial Dam (photograph 15), circular and rectangular sluiceway entrances, a fish trap proposed for the Columbia River immediately downstream from the Grand Coulee Dam, and many others.

Models based on the so-called "electric-analogy" were used to supplement some of these tests. The electric-analogy utilizes the flow of electric current through an electrolyte shaped to resemble the hydraulic structure for determining the idealized streamline flow through that structure. It is applicable only to certain types of problems in which boundary conditions are easily established; for such problems its simplicity and rapidity make of it an extremely useful tool.

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PRESENT LABORATORY OPERATIONS

Because practically every problem studied in the Bureau of Reclamation laboratories relates to the specific design of an actually proposed structure, the work of the laboratories has become a highly specialized field of hydraulics. Since complete similitude between models and their prototypes is impossible of attainment, the laboratory staff must be thoroughly familiar with the model limitations and with the corrections that should be applied to obtain results applicable to field conditions. To avoid the effects of viscous friction, which cannot be represented to scale, care must be exercised to prevent the construction of models on too small a scale. Again, to compensate for differences in wall and bottom friction, it is sometimes necessary to exaggerate model slopes.

The use of models has proven so advantageous in indicating opportunities for reducing costs and improving hydraulic properties that the work of the laboratories is now recognized as a regular part of hydraulic design. At the present time, the three laboratories are engaged in testing or constructing models of twenty different features relating to ten major projects. However, opposed to the tendency toward an increasing use of models is the fact that the accumulating experience, in many cases, obviates the necessity for further experiments so that any attempt to predict the future expansion of this work would be unwarranted.

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[illegible] TESTS BY BUREAU

SPILLWAYS

DAM	PROJECT	TYPE OF DAM	TYPE OF SPILLWAY	TYPE OF SPILLWAY GATES	TYPE OF STILLING POOL	MAXIMUM DISCHARGE SECOND-FEET	SCALE OF MODEL
der	Boulder Canyon, Ariz.-Nev.	Concrete gravity arch	[illegible]	None	Original stream bed	100,000	1:60
ee	Owyhee, Oreg.	do	do	Ring gate	do	80,000	1:48
on	Sun River, Mont.	Massive concrete arch	do	Six radial gates	do	80,000	1:53.6
hoe	Casper-Alcova, Wyo.	Concrete arch	do	Ring gate	do	50,000	1:60
der	Boulder Canyon, Ariz.-Nev.	Concrete gravity arch	Two side-channel spillways	Drum gates	do	400,000	1:100,1:60,1:20
Lake	Moon Lake, Utah	Earth fill	Side-channel	None	Spreading jet	10,000	1:40
or Park	Uncompahgre, Colo.	do	do	do	Original stream bed	10,000	1:50
nd Park	Upper Snake, Ida.	do	Double side-channel	do	do	5,000	1:30
d Coulee	Columbia Basin, Wash.	Concrete gravity	Overfall	Drum gates	Bucket type	1,000,000	1:134,1:120,1:40,1:80
en	Madden Dam, Canal Zone	do	do	Drum gates	Sloping apron with triangular sill	240,000	1:72
ris	Tenn. Valley Auth., Tenn.	do	do	Drum gates	Combination sloping and horizontal aprons with triangular sill	200,000	1:72
shall Ford	Colorado River, Tex.	Concrete gravity	Overfall	None	Combination sloping and horizontal aprons with triangular sill	350,000	1:40.9
eler	Tenn. Valley Auth., Tenn.	do	do	Radial gates	Sloping apron with diffusion sill	650,000	1:36
erial	Boulder Canyon, Ariz.-Nev.	Hollow reinforced concrete	do	None	Combination sloping and horizontal aprons with spreader teeth and sill	134,000	1:30,1:40
se Mesa	Salt River, Ariz.	Concrete arch	Overfall with auxiliary tunnel spillway	Radial gates	Original stream bed	100,000	1:90
wart Mountain	do	do	Open superelevated channel	do	do	180,000	1:100,1:60
osevelt	do	Masonry arch gravity	Overfall	do	do	150,000	1:100
lum	Yakima, Wash.	Earth fill	Open rectangular chute	Radial gates	Horizontal apron with sill	40,000	1:50
[illegible]	Humboldt River, Nev.	do	do	Radial gates	Horizontal apron with spreader step and rectangular sill	20,000	1:60
cova	Casper-Alcova, Wyo.	do	do	Stoney gates	do	55,000	1:72
allo	Rio Grande, N. Mex.	do	do	Radial gates	Horizontal apron with spreader teeth and sill	35,000	1:60
ll Lake	Riverton, Wyo.	do	do	do	do	10,000	1:30
amogordo	Carlsbad, N. Mex.	do	do	do	do	56,000	1:64
ley	[illegible] River, Oreg.	do	do	do	do	10,000	1:36
on Lake	Moon Lake, Utah	do	do	do	do	10,000	1:60
tlett	Salt River, Ariz.	Concrete arch and buttress	Open superelevated channel	Stoney gates	Original stream bed	175,000	1:100
[illegible] Flat	do	Concrete arch	do	do	do	150,000	1:90
[illegible]	[illegible] River, Utah	Earth fill	Open trapezoidal chute	Radial gates	Horizontal apron with sill	10,000	1:30
[illegible] allow	[illegible] Oreg.	do	do	do	Horizontal apron with spreader step and sill	11,700	1:30
[illegible]	[illegible]	do	do	do	Horizontal apron with spreader step	6,170	1:48
minoe	Casper-Alcova, Wyo.	Concrete arch	Tunnel	Stoney gates	Original stream bed	50,000	1:60

OUTLET WORKS

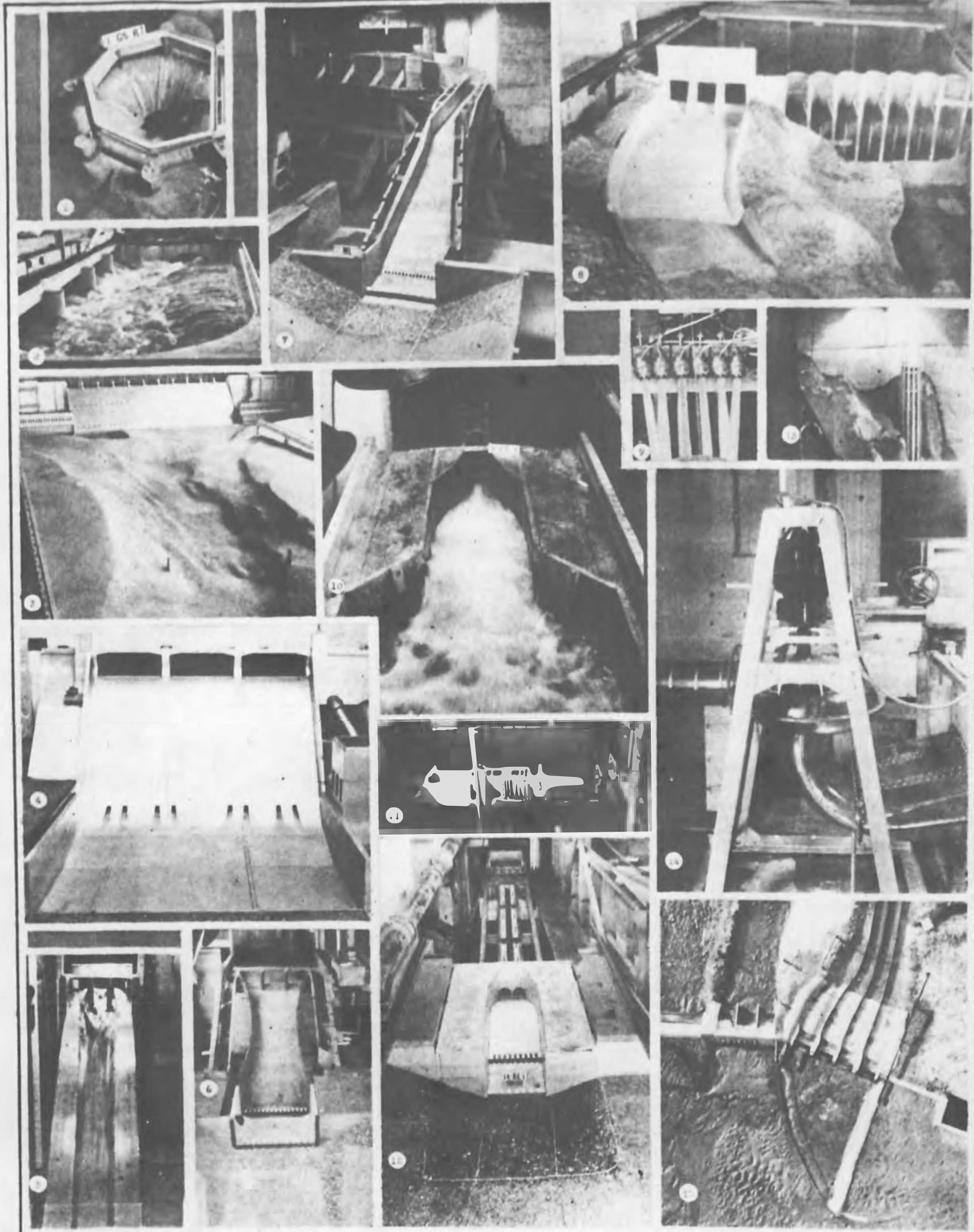
DAM	PROJECT	TYPE	TYPE OF CONTROL GATES	TYPE OF STILLING POOL	CAPACITY SECOND-FEET	SCALE OF MODEL
lder	Boulder Canyon, Ariz.-Nev.	Two 50-foot circular	Six needle valves per tunnel	Original stream bed	22,000 per tunnel-plug outlet	1:10[illegible].2,1:60,1:20
lcova	Casper-Alcova, Wyo.	One 20-foot circular with horizontal bend	Two needle valves	Depressed horizontal apron	5,000	1:40
ballo	Rio Grande, N. Mex.	One 13.5-foot horseshoe with Venturi meter	Two vertical slide gates	Horizontal apron combined with hump spreader teeth and sill	6,250	1:30
ull Lake	Riverton, Wyo.	Two 9-foot horseshoe	Four vertical slide gates	do	4,000	1:30
Owyhee	Owyhee, Oreg.	One 16-foot horseshoe with rectangular Venturi meter	do	None required	1,[illegible]	1:24
iant	Central Valley, Calif.	Four 110-inch conduits	Four needle valves	Level horizontal apron	[illegible]	1:34.3

INTAKE TOWER

DAM	PROJECT	TYPE OF INTAKE	TYPE OF GATES		CAPACITY SECOND-FEET	SCALE OF MODEL
lder	Boulder Canyon, Ariz.-Nev.	Four [illegible]-foot vertical towers	Two cylinder gates per tower		23,000 per tower	1:64

HYDRAULIC TURBINES

DAM	PROJECT	TYPE, SIZE, [illegible]	HEAD	TYPE OF [illegible]	PURPOSE OF TEST	CAPACITY SECOND-FEET	SCALE OF MODEL
eeler	Tenn. Valley Auth., Tenn.	Propeller, 22.4-foot dia., 50,[illegible] hp.	50 feet	[illegible]	Draft tube efficiencies	10,[illegible]	1:50
[illegible] Coulee	Columbia Basin, Wash.	Propeller, [illegible]-foot dia., 1[illegible]	335 feet	do	[illegible]	[illegible].4	1:24



MODELS OF VARIOUS HYDRAULIC STRUCTURES

1, Glory-hole spillway, Gibson Dam; 2, Side channel spillway, Boulder Dam; 3, Overfall section, Grand Coulee Dam; 4, Overfall section, [illegible] Dam; 5, Tunnel spillway, Seminoe Dam; 6, Open chute spillway, Alamogordo Dam (earth fill type); 7, Open chute spillway with curve, [illegible] Dam (earth fill type); 8, Open chute spillway with superelevated curve, Bartlett Dam; 9, Battery of six needle valves, tunnel [illegible] outlet [illegible] Dam; 10, Outlet tunnel and stilling pool, Caballo Dam; 11, Venturi meter in irrigation tunnel, Owyhee Dam; 12, Outlet tunnels and stilling pool, [illegible] Dam; 13, Intake tower, [illegible] Dam; 14, Hydraulic turbine, Grand Coulee Dam; 15, River Model of Imperial Dam, Spillway and All American Canal intake structure.