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Checking Arch Dam Designs with Models

Results of Tests on Small-Scale Models of the Stevenson Creek and Gibson Arch Dams

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A REMARKABLE similarity has been found between measured deflections of the full-sized Stevenson Creek Test Dam and those calculated from the deflections of a 1:12-scale model tested with a mercury load. Data taken on a 1:68-scale model of the Gibson Dam, under mercury load and with extreme temperature changes, checked closely with the results of an analysis of the model by the trial load method. If tests made on models can be relied upon to correctly reveal the conditions in their full-sized prototypes, and if mathematical calculations based on a properly conceived theory check these tests, a great step will have been made toward building safe and economical high arch dams.

During the summer of 1927, the Bureau of Reclamation, in cooperation with the Engineering Foundation's Committee on Arch Dam Investigation and the University of Colorado, began a comprehensive program of experimental work on small-scale models of arch dams. The purpose of the tests was to supply definite information regarding the safety of arch dams already built or now being constructed by the Bureau of Reclamation; to check the trial load method of designing arch dams as developed and used by the bureau during the past six years; to demonstrate the feasibility or infeasibility of using small-scale model tests in planning costly arch dam structures; and to provide the complicated technical data needed for comprehensive engineering studies of deformations and stress distribution in arch dams, particularly in the 727-ft. Hoover Dam on the Colorado River near Las Vegas, Nev., the contract for which has just been awarded.

Thus far, the results obtained have been very satisfactory. Although they have by no means solved all the complicated problems involved in arch dam design, they have established the accuracy of the trial load method of analysis and have made possible a more exact, and consequently a more economic design of arch dam structures.

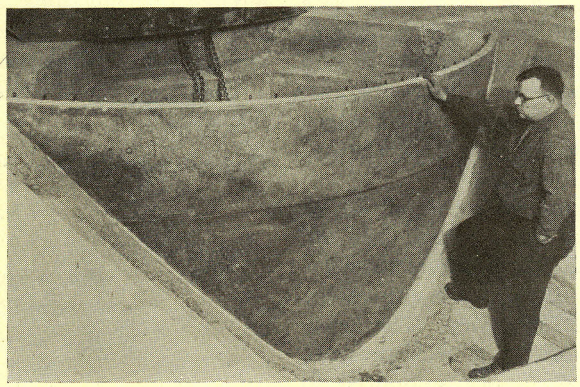
Experimental Pit of Reinforced Concrete

As the first step in this comprehensive program of tests, an experimental pit was built, in June 1927, beneath the floor of the Testing Materials Laboratory of the University of Colorado, Boulder, using local aggregates and a mix of approximately 1:2:4 proportions. In Fig. 1 is shown the plan and a section of the pit, which has a depth of 5 ft., a maximum inside length of 18 ft., and a maximum inside width of 12 ft. The octagonal, stepped design permits the testing of models of practically any shape, symmetrical or unsymmetrical, and of practically any size not exceeding the maximum inside dimensions of the pit.

For any particular test, the shape of the pit is altered to that of the dam site under consideration by building up a supplemental base of concrete, or of the material to be used in the model. In order to secure the greatest similarity between the model and the full-sized dam, it is desirable to have the ratio of the moduli of elasticity of the model and the supplemental base the same as that of the concrete and abutment rock of the full-sized structure.

So that it would be possible to tie the walls of the pit together in case of undesirably large abutment deformations, 25-lb. rails, bent in the shape of a U, were included as vertical reinforcement along the longitudinal center line of the pit and at locations $2^1/_2$ ft. on each side of the transverse center line. The ends of the rail were allowed to project 6 in. above the tops of the walls.

On January 11, 1928, the supplemental base was poured for the model of the Stevenson Creek Test Dam, the 60-ft. concrete arch built by the Engineering Foundation's Committee on Arch Dam Investigation at Big Creek, Calif. In pouring the base, local aggregates and cement were used, mixed by volume in the proportions of approximately 1:2:3. Before pouring the model the top of the base was roughened by chipping out a groove along the location of the contact surface. For the model,



Upstream Face of Model of Stevenson Creek Test Dam
The Horizontal Line Is a Steel-Form Joint Mark

which was poured on March 22, 1928, fine aggregate shipped from the Stevenson Creek Test Dam was mixed with local cement in the proportions of 1:3.25, by weight.

No coarse aggregate was used because of the comparatively thin section of the upper half of the model, which was uniform from abutment to abutment at all elevations, and only 2 in. in amount. The water–cement ratio was 1.0, and the average slump 9.1 in. A fairly wet mix was necessary so that the concrete would flow through the tremie to the bottom of the forms and fill all spaces around the small deflection anchors at the downstream face, where no spading was possible.

A plan of the model, the developed downstream elevation, and the maximum cross section are shown in Fig. 2. Invar bars for measuring abutment movements were placed at elevations corresponding to those at which similar measurements had been made for the full-sized dam. Likewise, deflection anchors for attaching dials to measure the radial deflections were located at vertical and horizontal sections corresponding to those investigated at the dam.

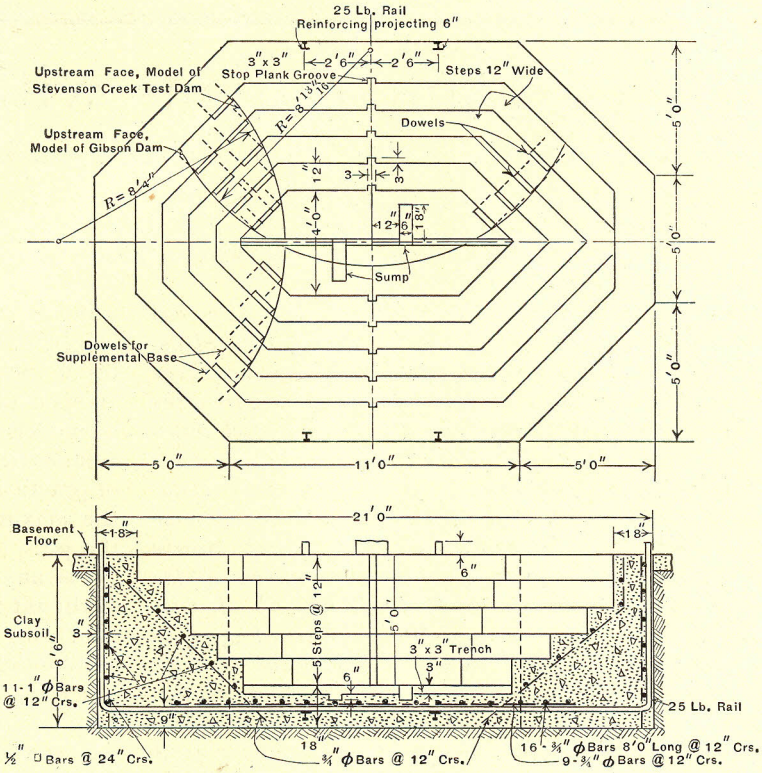


FIG. 1. EXPERIMENTAL PIT FOR MODEL TESTS OF ARCH DAMS
University of Colorado Testing Laboratory, Boulder

WORK OF TESTING

This model of the Stevenson Creek Test Dam was tested under concentrated radial loads applied at the center line; under a triangular water load; under a triangular mercury load; and, finally, under a water pressure which was gradually increased until failure occurred. Water and mercury loads were applied in a rubber bag in all cases (Fig. 2), and tests were made for partial depths of load as well as for full depths in the case of the triangular loads. Since mercury is 13.6 times as heavy as water, the application of the triangular, full-depth, mercury load to the 1:12-scale model was a slightly more severe test than the application of the full reservoir water load to the full-sized dam.

In the test to destruction, failure of the upper 25 in. of the model, above a horizontal crack which had developed during the mercury-load tests, occurred under a water pressure of 25 lb. per sq. in., which is equivalent to that caused by a head of 59 ft. of water. The lower part of the model did not fail at all. The total pressure on the upper part at the time of failure amounted to approximately 37 tons, or about 5.3 times as much load as was carried during the full-depth mercury test. Failure occurred by the sliding of the upper portion of the model up one abutment.

The water-load tests were made before the mercury tests and before any cracking occurred, except for some minor cracks at the lines of contact between the model and the abutments, which developed during the curing period when the model was not being sprinkled. As soon as the abutment cracks were noticed, sprinkling was begun and was continued throughout the testing work. Since the full-sized dam was cracked, and since the mercury load produced cracks in the model very similar to those in the dam, the results of the water-load tests, although furnishing much valuable data, did not check the measurements at the dam as well as the mercury-load tests.

Observations made during the mercury-load tests included measurements of radial deflections, changes in chord lengths, spreading of abutments, the opening of a crack at the upstream edge of the base of the crown section, changes in mid-ordinates, and horizontal, vertical, and diagonal strains at the downstream face. Changes in mid-ordinates and strains at the downstream face were measured with an optical strain gage. Other deformations and radial deflections were measured with 0.0001 dials.

A comparison between the measured, radial deflections at the full-sized dam and those indicated by the full-depth mercury tests on the model is given in Fig. 3. It will be noticed that the two curves are in very close agreement in all parts of the structure. A slight difference in deflections occurs at the quarter points, but the deflections at the crown section are almost in exact agreement at all elevations.

Deflections were calculated and compared using the formula:

$$\text{Deflection of dam} = \frac{Em}{\delta\, n^2\, E_d} \times \text{deflection of model}$$
$$= 8.588 \text{ deflection of model,}$$

where

Em = modulus of elasticity of model = 2,920,000 lb. per sq. in.

E_d = modulus of elasticity of dam = 3,600,000 lb. per sq. in.

δ = density of mercury = 13.6

n = scale of model = 1/12

A model was also constructed of Gibson Dam, the 200-ft. concrete arch completed in 1928 on the Sun River Project of the Bureau of Reclamation, in Montana. The supplemental base was poured February 13, 1929, using local materials mixed in the proportions of $1:2^1/_2:2^1/_2$. That part of the top surface which would later be in direct contact with the base of the model was stepped so as to obtain a bond which would prevent sliding such as caused the failure of the model of the Stevenson Creek Test Dam.

POURING THE MODEL OF GIBSON DAM

On March 5, 1929, the model was poured, using a concrete mix of $1:2^1/_2:2$, by weight; a water–cement ratio of 1.0; and an average slump of 6.5 in., a fairly wet mix being necessary in order to get the concrete around the small deflection anchors near the bottom of the model where no spading was possible. The cement, sand, and gravel for building the model were shipped from the dam. The sand was 50 per cent natural and 50 per cent manufactured, thoroughly mixed, and the aggregate was pea gravel which would pass a $^3/_8$-in. sieve. No coarser material could be used because of the comparatively small dimensions of the model. Seven batches of concrete were required, but since the pouring was continuous there were no construction joints in the finished structure, either horizontal or vertical. The model was sprinkled continuously during the curing process and also during the tests.

An illustration shows the model soon after the tests were begun, the rubber bag and steel plate being moved back so as to expose the upstream face. The white patches at the downstream face are places where the concrete happened to be dry at the time the photograph was taken. Dials for measuring radial deflections, and invar bars and dials for recording the spreading of the abutments and changes in chord lengths can be seen at the downstream side. In Fig. 4 is shown a crown cross section, and details of the mercury supply tank and piping.

For the full-depth mercury test the maximum radial deflection was only 0.0015 in., or only 15 divisions on the measuring dial; while the maximum strain at the downstream face was only 14 millionths in. per in. Nevertheless, very satisfactory data were secured, and the results were found to check very closely with those calculated in the analysis of the model by the trial load method.

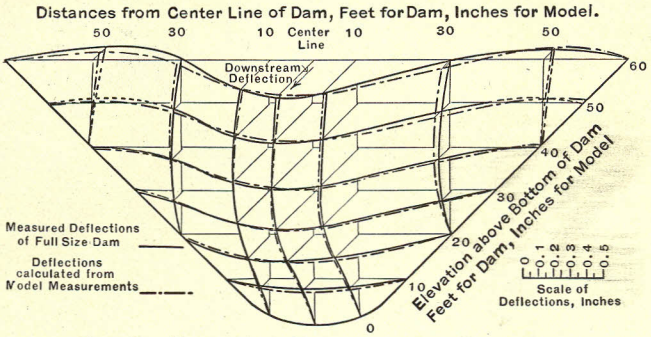


Fig. 3. Stevenson Test Dam and Its Model
Deflections Compared Under Full-Depth Loads

In Fig. 5 is shown a comparison of the stresses measured at the downstream face of the model with those calculated by the trial load method, assuming a straight line distribution of stress and making proper allowances for radial movements, tangential sheer, and the effects of twist and Poisson's ratio. It will be noticed that the calculated stresses are in very satisfactory agreement with the measured stresses at all elevations, in both arch and cantilever elements. Such differences as do exist would be practically eliminated if corrections were made for the non-rectilinear distribution of stress.

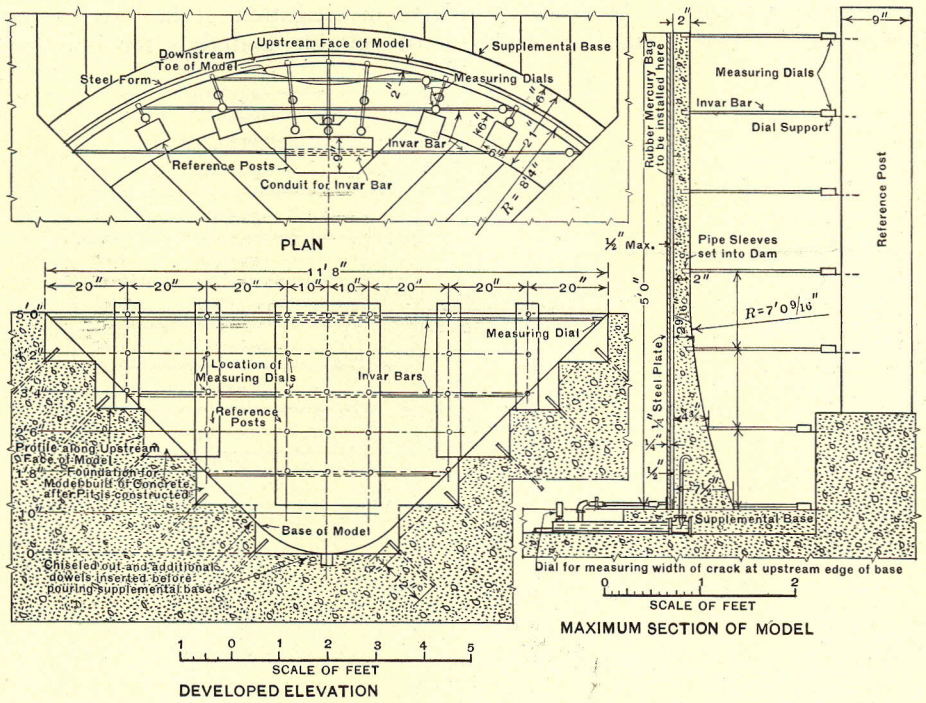


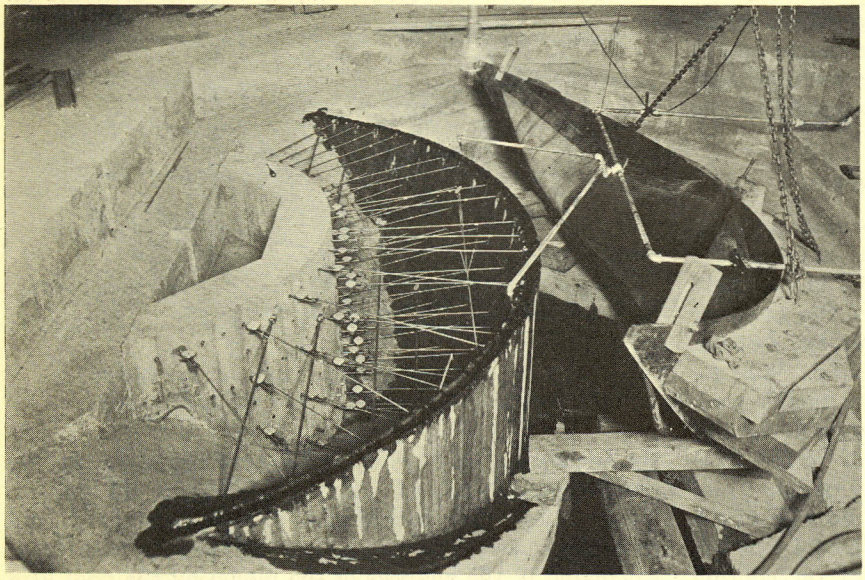
Fig. 2. Model of the Stevenson Creek Test Dam
Scale of Model 1:12

TEMPERATURE TESTS OF GIBSON MODEL

After the mercury-load tests were completed, the model of Gibson Dam was subjected to an elaborate and extremely severe temperature test, changes being produced by means of a sprinkling system at the top of the model, through which hot, temperate, or cold water could be supplied as desired. A separate sprinkling system at the ends of the model, supplied with hydrant water, kept the abutments and foundation at a comparatively uniform temperature, regardless of the temperatures within the model.

A total of 59 thermometers, inserted at different depths in the model and in the abutment concrete were used. Radial deflections were measured with 0.0001 dials,

as in the mercury load tests, but owing to the nature of the tests it was not feasible to make direct measurements of strains. The total range in the average temperature of the model obtained during the tests was about 27 deg.



MODEL OF GIBSON DAM—RUBBER BAG AND STEEL PLATE MOVED BACK
Deflection Dials in Place at Downstream Face

cent., from a minimum value of about 8 deg. cent. to a maximum of about 35 deg.

The purpose of the temperature test was to secure an additional, independent check on the trial load method of analyzing arch dams. It was realized that the total range in concrete temperatures obtained in such a test would be much greater than the maximum seasonal changes in a dam as large as Gibson. However, it was believed that an extreme test would furnish a better check on the complicated mathematical processes involved in the trial load analysis than would one more nearly representative of field conditions.

The trial load analysis of the model for the temperature test included the restraining effect of the cantilever elements, the effects of tangential sheer and of twist, and was made for the conditions existing at the time of maximum temperature drop. A comparison of the calculated and observed radial deflections for one of the horizontal elements is given in Fig. 6. Calculated curves are shown for the different steps involved in the analysis, so that the effects of the various restraining actions can be visualized.

These curves show that the final calculated deflections are very nearly the same as the observed deflections. What little discrepancy still exists would be nearly eliminated by making proper allowances for the modifying effects of Poisson's ratio. One of the principal things indicated is the very marked effect of the restraining action of the cantilevers. This effect is represented by the difference between the curves marked "deflection of free arch" and those marked "first radial adjustment."

MATERIALS FOR BUILDING MODELS INVESTIGATED

Very complete laboratory tests of the concrete used in the models of Gibson and of Stevenson Creek Test Dam were made, primarily to determine the values of the elastic properties involved in the analyses of the models. Probably two of the most unusual features connected with the concrete tests were the measurements of flow in flexure and ultimate strength in torsion.

Tests on the model of Gibson Dam, although furnishing satisfactory data under the full-depth mercury load, showed conclusively that for larger dams it would be advisable to build models out of materials having definitely lower moduli of elasticity than concrete. This is especially true for the Hoover Dam, the design for which it is desired to check by model tests.

After an exhaustive investigation, it has been concluded that the most suitable materials for building small models of large dams are celluloid, or a mixture of plaster of paris and celite. The plaster of paris and celite mixtures necessary to obtain moduli of elasticity less than 250,000 lb. per. sq. in. have comparatively low unit weights. Some of the mixtures tested had unit

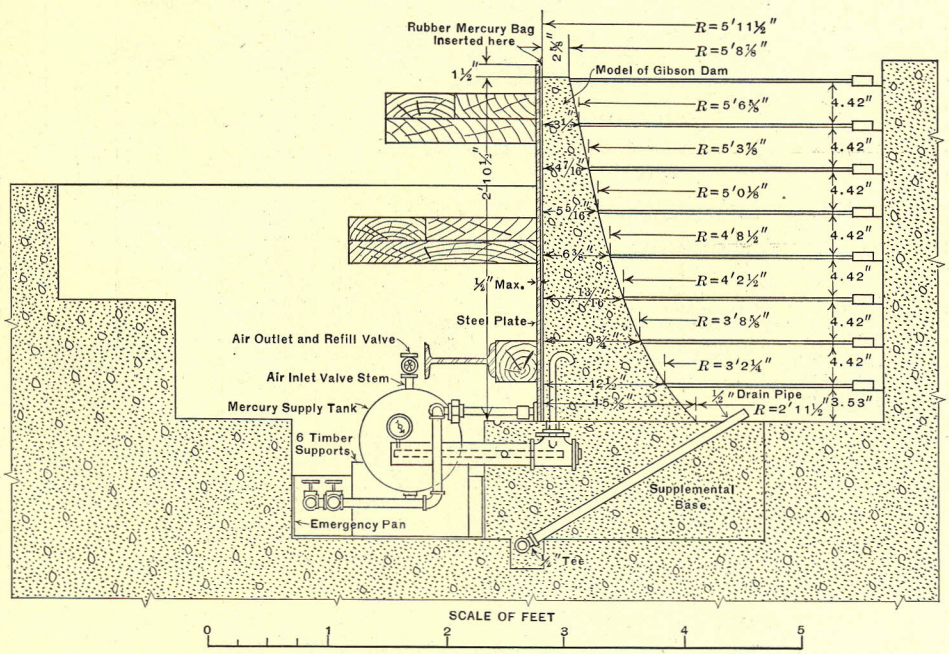


FIG. 4. MODEL OF GIBSON DAM
Arrangement of Test, Scale 1:68

weights as low as 30 lb. per cu. ft. However, it was found entirely feasible to increase these to approximately that of concrete by simply adding proper proportions of small shot to the mixture. Although the presence of the shot seemed to increase the modulus of elasticity slightly, it was still possible to obtain practically any modulus desired by using the proper proportions of plaster and celite. The use of shot will probably be found advisable in cases where it is desired to duplicate as closely as possible the action of the cantilever elements.

MODELS OF HOOVER DAM

At the present time the Bureau of Reclamation is building a plaster of paris and celite model of Hoover Dam, using proportions which will give a modulus of elasticity of from 125,000 to 150,000 lb. per sq. in. It was not considered necessary to use shot in the mixture in this case inasmuch as there is a very heavy vertical mercury load on the upstream face of the model. In fact, due to the upstream batter and the resulting vertical water load, no tension would occur at the base of the crown cantilever section of the full-sized Hoover Dam if the concrete had no weight at all.

At the base of its maximum cross section, this model will be $36^3/_8$ in. high and $32^1/_2$ in. thick. It is being built up in horizontal layers $2^1/_2$ in. thick, each joint being provided with keys to give satisfactory bond. The surface of each layer is waterproofed with shellac or varnish, so as to prevent the absorption of moisture from above when the next layer is poured.

It is also planned to manufacture and test a celluloid model of Hoover Dam, to be 29 in. high and 26 in. thick at the base of the crown section. This model will have a modulus of elasticity of approximately 260,000 lb. per sq. in. and will consequently require somewhat more refined measurements of deformations than are necessary in the case of the plaster of paris and celite model.

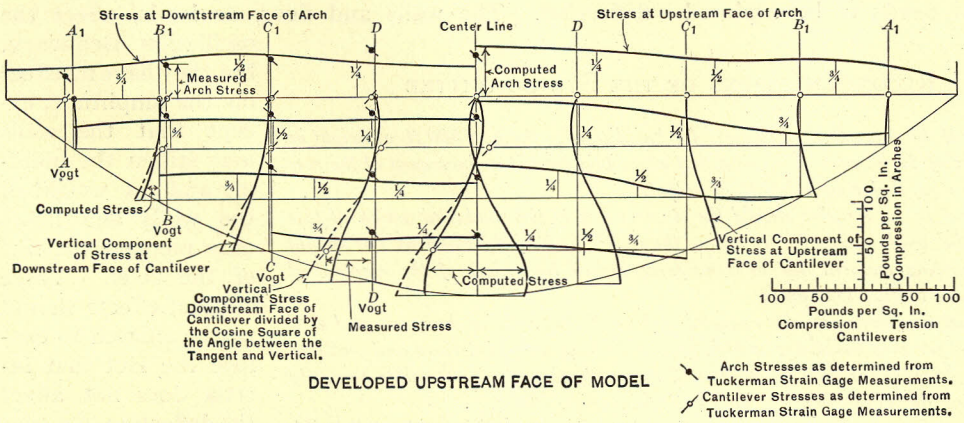


Fig. 5. Model of Gibson Dam
Stress Measurements and Trial-Load Calculations Compared

Results of the various measurements, together with a more detailed description of these experiments, will be given in the progress report of the Engineering Foundation's Committee on Arch Dam Investigation, which is to be published in the near future. Members of the profession are invited to participate in a full discussion of this model work and its application to Hoover Dam.

A sub-committee on model tests, appointed by Chairman Charles D. Marx of the Engineering Foundation's committee, is cooperating with the representatives of the Bureau of Reclamation in outlining, supervising, and conducting the investigations. This sub-committee is composed of J. L. Savage, M. Am. Soc. C.E., Chief Designing Engineer of the Bureau of Reclamation, Chairman; George E. Beggs, M. Am. Soc. C.E., Pro-

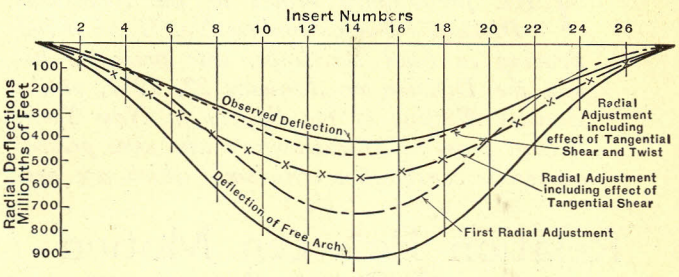


Fig. 6. Model of Gibson Dam
Temperature Deflections, Observed and Calculated

fessor at Princeton University, Princeton, N.J.; Raymond E. Davis, M. Am. Soc. C.E., Professor at the University of California, Berkeley; F. R. Dungan, C. L. Eckel, and H. J. Gilkey, all Members Am. Soc. C.E., and professors at the University of Colorado, Boulder; D. C. Henny, M. Am. Soc. C.E., Consulting Engineer of Portland, Ore.; Julian Hinds, M. Am. Soc. C.E., Chief Designing Engineer of the Metropolitan Water District, Los Angeles; Ivan E. Houk, M. Am. Soc. C.E., Senior Engineer of the Bureau of Reclamation, Denver; Fred A. Noetzli, M. Am. Soc. C.E., Consulting Engineer of Los Angeles; W. A. Slater, M. Am. Soc. C.E., Professor at Lehigh University, Bethlehem, Pa.; and Fredrik Vogt, Assoc. M. Am. Soc. C.E., Professor at Norges Teknishe Hoiskole, Trondhjem, Norway.

The tests on the model of the Stevenson Creek Test Dam and the mercury-load tests of the model of Gibson Dam were made by Professor Vogt, who was at that time employed by the Bureau of Reclamation. The auxiliary concrete tests are being conducted under the direction of Professor Gilkey of the University of Colorado. The temperature tests of the model of Gibson Dam and the tests of materials for use in building a model of Hoover Dam were made by A. W. Simonds, M. Am. Soc. C.E., Engineer, who is now in direct charge of the work on models of Hoover Dam. The experimental program has been supervised throughout by Mr. Houk and Mr. Savage.

All engineering and construction work of the Bureau of Reclamation is under the direction of R. F. Walter, M. Am. Soc. C.E., Chief Engineer, with headquarters at Denver, and all activities of the bureau are under the general direction of Elwood Mead, M. Am. Soc. C.E., Commissioner of Reclamation, with headquarters at Washington, D.C.