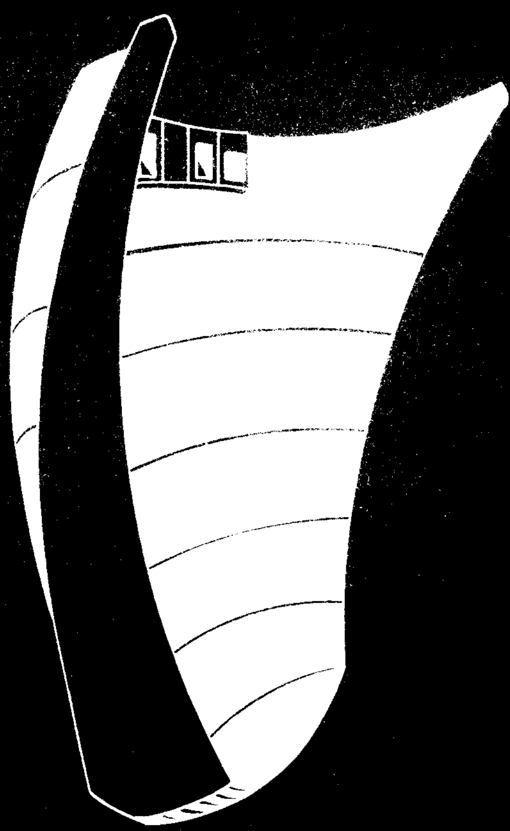
Structural Model Tests of Arch Dams-Glen Canyon and Morrow Point Dams



A Water Resources Technical Publication

RESEARCH REPORT NO. 16

United States Department of the
INTERIOR
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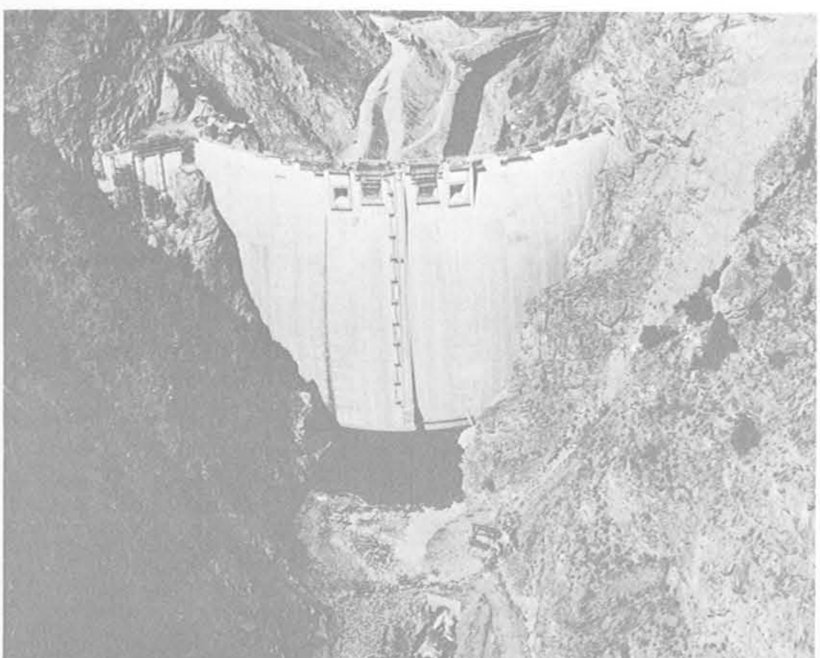
Glen Canyon Dam.

Morrow Point Dam.



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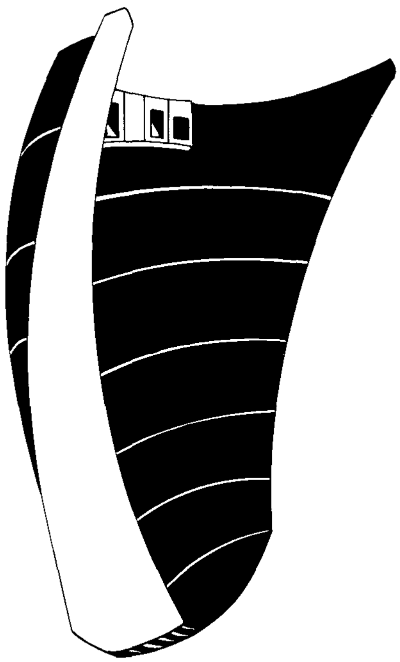

Structural Model Tests of Arch Dams-Glen Canyon and Morrow Point Dams

By George C. Rouse
William T. Lockman
James A. Stubbs
Office of Chief Engineer

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

As the Nation's principal conservation agency, the Department of the Interior has basic responsibilities for water, fish, wildlife, mineral, land, park and recreational resources. Indian and Territorial affairs are other major concerns of America's "Department of Natural Resources."

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PREFACE

This report describes specific Bureau of Reclamation uses of structural dam models, which are essentially analog computer devices. Model materials, construction, loading and testing are discussed, and results from tests on Glen Canyon and Morrow Point Model Dams are documented. The booklet is amply illustrated with photographs, diagrams, and bibliography to support the text.

The information and data can be of interest and value to all concerned with the structural behavior of concrete dams and in the correlation between results from model studies and those compiled from trial-load analysis. The report is also useful for academic studies.

The authors acknowledge the assistance of members of the Dams Branch, Division of Design, who participated in the structural model studies of Glen Canyon and Morrow Point Dams: S. Camins, D. J. Helstrom, F. C. Ladd, E. G. Massaro, D. L. Misterek, and L. H. Roehm. L. R. Callewyn, J. E. Kloer, and F. J. Kuhn of the Bureau of Reclamation laboratory shops assisted with the fabrication of the models. Computed stresses and deflections for the Glen Canyon and Morrow Point models were furnished by the Analysis Unit of the Concrete Dams Section. Liaison between the Division of Research and the Division of Design was provided by L. J. Mitchell and G. L. Butler during the construction and testing of the models.

Included in this publication are an informative abstract and list of descriptors, or keywords, and identifiers. The abstract was prepared as part of the Bureau of Reclamation's program of indexing and retrieving the literature of water resources development. The descriptors were selected from the *Thesaurus of Descriptors,* which is the Bureau's standard for listings of keywords.

Other recently published Water Resources Technical publications are listed on the inside back cover of this report.

CONTENTS

FIGURES

INTRODUCTION

A structural model is a device which may be used to predict the behavior of the structure it represents. In a sense, it is a type of analog computer.

Models have been used for about 60 years to investigate the effects of static and transient loadings on many types of structures, such as: mass concrete dams; thin-shell roofs; frame structures, including buildings and water tanks; suspension and other types of bridges; and airframes. Some of these structures have been analyzed for dead and live loads; others, for loadings produced by wind, earthquake, and the effects of temperature gradients. Whatever the type of loading, structural models afford a practical means of obtaining information on stresses, strains, deflections, rotations, or moments to which a structure may be subjected.

Investigations of the behavior of concrete dams by model analysis techniques are performed for a variety of reasons. Some of these are:

1. To design dams; that is, to establish this final shape of a dam.

2. To check stresses and deflections found by mathematical analysis methods. When this is done, the shape of the dam is usually based on the results of numerical computations.

3. To investigate local stresses in dams; for example, stresses around openings for penstocks and orifice spillways.

4. To study the validity of assumptions used in the design of dams, such as those made in the computation of temperature gradients, seismic loadings, and foundation and abutment deformations.

5. To estimate the factor of safety of a dam.

Bureau of Reclamation designs of concrete dams are based on the analytical method of trial loads; models may be used when a check is desired on computed stresses and deflections. However, the reverse is generally true for dams designed in Europe. There, the initial shape of a dam is found by analytical methods, and the final shape is determined by model testing.

As stated, a structural model is a type of analog computing device; consequently, it must be constructed and loaded to meet certain conditions, referred to as conditions of similarity. For a hydrostatic type of loading, the similarity conditions are:

1. A model should be geometrically similar to the dam.

2. The ratio of the pressure applied to any point on a loaded face of a model to the pressure applied to the corresponding point on the prototype should be constant.

3. The ratio of the modulus of elasticity of the supporting rock to the modulus of elasticity of the concrete in the dam should be maintained for the moduli of elasticity of the materials used in similar locations in the model.

4. Poisson's ratio for the model material should be the same as the material used to construct the prototype.

5. The model should be constructed, insofar as practicable, from uniformly elastic materials.

With regard to this last condition, it is important to note that a model dam is not a true representation of the prototype, but, rather, it represents an idealized structure; that is, it represents a dam constructed from an elastic, isotropic, homogeneous material which is free from discontinuities. Actually, neither the concrete in the dam nor the rock on which it rests satisfies these conditions.

The first use of models to make structural analyses of dams was about 60 years ago in England by Messrs. Wilson and Gore [1].* The models used for these investigations were made from rubber. From that time until 1928, no model investigations of dams were reported. During 1928 and 1929, concrete models of Stevenson Creek Test Dam and Gibson Dam were constructed and tested by the Bureau of Reclamation at the Civil Engineering Laboratories of the University of Colorado [2]. Since the investigations on these two models yielded satisfactory results, the Bureau of Reclamation decided to continue the development of

*Bracketed numbers relate to references listed in the back of this report.

model testing techniques. Continued model investigations were begun with experimentation on model materials. As a result of this work a new model material, plaster-celite, was developed [3]. This material is still being used extensively throughout the world to build structural models. From 1930 to 1937, nine 3-dimensional or sectional models of dams were built and tested by the Bureau of Reclamation at the University of Colorado. During this period, tests were made on four models of Hoover Dam and two of Grand Coulee Dam [3, 4].

Structural model analyses of mass concrete dams were practically discarded from 1937 until after World War II, when many European countries started development of large-scale hydroelectric power projects. In connection with this work, high concrete arch dams were required. To design these structures, European engineers favored model analysis rather than the analytical method of trial loads for reasons that, at that time, numerical computations involved in the trial-load or other accepted methods of analysis were time-consuming, that structural models could be built and tested by an organization staffed by technicians rather than engineers, and that the fabrication and testing of structural models is the type of work in which Europeans excel.

During initial experimentation on models, the techniques used by the Europeans in constructing and testing models were similar to those developed by the Bureau of Reclamation. However, as the Europeans gained experience, new procedures were devised for constructing, loading, and testing model dams. Concurrent with these advances, new laboratories were built especially for this work, such as those at LNEC [1] in Lisbon, Portugal [5], and ISMES [2] in Bergamo, Italy [6].

The Bureau of Reclamation resumed testing of structural models of concrete dams in 1958. At that time a structural model analysis of Glen Canyon Dam was begun. This structure is a 710-foot-high concrete arch located on the Colorado River upstream from Hoover Dam. Following completion of the Glen Canyon Dam model analysis, a model of Morrow Point Dam was built and tested. Morrow Point Dam, located on the Gunnison River near Montrose, Colo., is a double-curvature concrete arch, 468 feet high.

This report describes the techniques used in constructing and testing these two models. Also included in the report are comparisons of measured with computed results.

[1] Laboratorio Nacional de Engenharia Civil.
[2] Instituto Sperimentale Modelli e Structure.

MODEL MATERIALS

Five materials have been used to construct models of mass concrete dams: concrete, rubber or rubber litharge, alkathene, portland cement and pumice, and plaster-celite. Concrete was used by the Bureau of Reclamation for the construction of the Gibson and Stevenson Creek models previously mentioned. Although concrete does not meet many of the specifications for model materials, a comparison of deflections measured on the Gibson and Stevenson Creek models with computed deflections was satisfactory.

Models of Calderwood [7] and Hoover Dams were constructed from rubber litharge. Rubber litharge possesses certain advantages as a model material. One of these is that measurable strains can be obtained when the model dam is loaded with water. However, this material is not considered satisfactory for structural models of dams for the following reasons: (1) it is nonisotropic, (2) it has a Poisson's ratio about twice that of concrete (0.5), and (3) the cement used to join the individual 1-inch-thick rubber sheets is toxic.

An alkathene model of Cabril Dam was constructed at the LNEC Laboratory in Lisbon. Alkathene, a polyethylene resin, has a high Poisson's ratio (0.5) and creeps under sustained model loadings [8].

Mixtures of portland cement and pumice have been used successfully for a number of years at the ISMES Laboratory in Bergamo for model dams [9] This material appears to be deficient on one count: it undergoes drying shrinkage. To control this shrinkage, ISMES models were sprayed with a polyvinyl compound immediately following removal of the forms.

At present, a mixture of plaster and "celite," a diatomaceous earth sometimes referred to as Kieselguhr, has been found to be the most satisfactory material for structural models of mass concrete dams. It has been used for that purpose in Portugal, France, and Japan, as well as in the United States. It meets, within practical limits, most of the required specifications outlined below, except the one pertaining to the requirement that model materials should be perfectly elastic. For extended periods of loading, greater than 1 hour, plaster-celite having a relatively low modulus of elasticity undergoes some creep. The effect of creep on test results is minimized by restricting the time of loading to approximately one-half hour.

Producing a model material which will meet the required specifications is to some extent a cut-and-try process. Often, many trial mixes and physical property tests have to be made before a model material having the desired properties can be found. This is particularly true for plaster-celite prepared from commercially available materials whose properties vary from sack to sack.

A material suitable for structural models of concrete dams should meet the following specifications:

1. It should be elastic for the entire range of the model stresses (comprehensive and tensile).
2. It should be homogeneous and isotropic.
3. It should have a Poisson's ratio equal to that found for mass concrete used in dam construction (approximately 0.2).
4. It should not shrink after taking its initial set.
5. Its modulus of elasticity should be subject to change by altering the proportions of the ingredients in the mix.

In addition to these specific requirements for an idealized model material, the material should also satisfy certain special requirements:

1. When shaping of a structural model is to be accomplished by carving and routing methods, the material should be sufficiently soft so that it can be easily cut by hand tools.
2. If bonded resistance wire (or foil) gages are to be employed for measuring strains, the surfaces of the model dam should be smooth and free from visible holes.
3. When mercury is to be used as a loading me-

329-437 O—69——2

dium, the moduli of elasticity of the model materials should be low enough so that maximum strains on the model faces will be at least 100 microinches per inch.

4. For model materials made up of plaster and a lighter inert material, such as celite, the mix should have a consistency of thick cream and a setting time between 20 and 30 minutes. These are optimum conditions. The setting time given represents the minimum time required for casting a model component having a volume of about 2 to 3 cubic feet. If a mix has the required consistency, plaster will not settle to the bottom of the pour, and no large air pockets will develop in the material.

PREPARATION OF PLASTER-CELITE MIXES

One of the principal reasons for making structural analyses of dams by means of models is to determine the effect of foundation and abutment deformations on the stresses in the dam. To obtain this information, model materials having different moduli of elasticity (E) have to be developed. One specification required in preparation of these materials is that

$$\frac{E(\text{model dam})}{E(\text{model foundation})}=\frac{E(\text{concrete})}{E(\text{rock})}$$

For the Glen Canyon and Morrow Point models the ratios of the moduli of elasticity for plaster-celite used in the model dam and its foundation were 6 to 1 and 1.6 to 1, respectively.

Preparation of two satisfactory plaster-celite mixes, one of which has a modulus of elasticity six times that of the other, often requires a considerable amount of experimentation. Difficulties sometimes arise not only in meeting the necessary mix specifications (including consistency and setting time), but also from the lack of uniformity in the mix ingredients. With regard to the range of E values for plaster-celite, it has been found that for mercury loadings, the material of the dam should have a modulus of elasticity less than 600,000 psi to obtain adequate deflection and strain indications; and the material in the abutments should have a modulus of elasticity greater than 75,000 psi to prevent excessive creep of the abutment material adjacent to the keyway.

Nonuniformity of the mix ingredients can occur in the following ways: variation in moisture content in the plaster and celite, inclusion of bentonite in commercial celite, and physical and chemical variations in the raw materials used in the manufacture of commercial plasters. In an attempt to solve the problem of nonuniformity of the ingredients in plaster-celite mixes for model dams, the Bureau of Reclamation used a gypsum-cement plaster manufactured especially for molding and pattern work and a celite which does not contain additives. As indicated in the list of materials for the model mixes given here, gypsum-cement plaster was not used for the plaster-celite in the Glen Canyon model.

Mixing of plaster-celite has been done in several ways. In Portugal and France, plaster-celite has been mixed in a round tank by means of a propeller-like device. The bottom of the tank was equipped with a discharge line and a pump to facilitate transportation of the mix to the molds. For the Glen Canyon and Morrow Point models, plaster-celite was mixed in a conventional electrically driven, paddle-type plaster mixer (figure 1). To reduce the number and size of air voids in the material used in the model dam, the mix was prepared under a partial vacuum.

Moduli of elasticity and Poisson's ratios of plaster-celite obtained for trial and model mixes were determined principally from compression tests on 3- by 6-inch cylindrical specimens. Test equipment used for this purpose were a longitudinal compressometer (figure 2), a lateral compressometer, and a compressed air testing machine (figure 3).

The longitudinal compressometer consisted of two magnesium-alloy rings, each of which was attached to cylindrical specimens by means of three support screws located at 120° intervals around the rings. Three Tuckerman optical strain gages, having 2-inch gage lengths, were mounted between the rings. By means

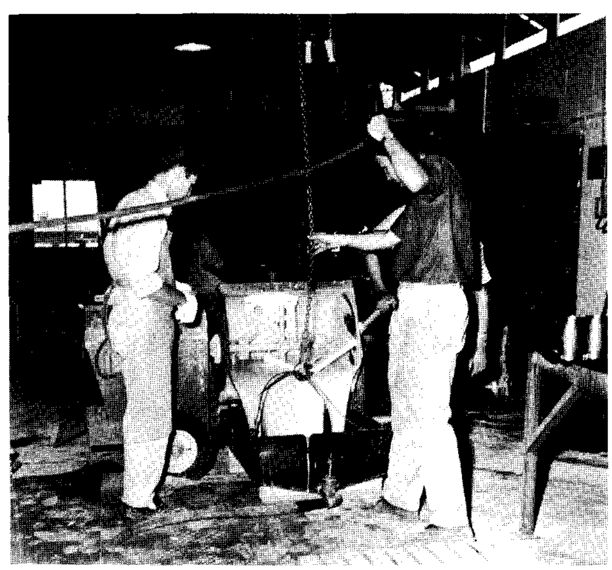
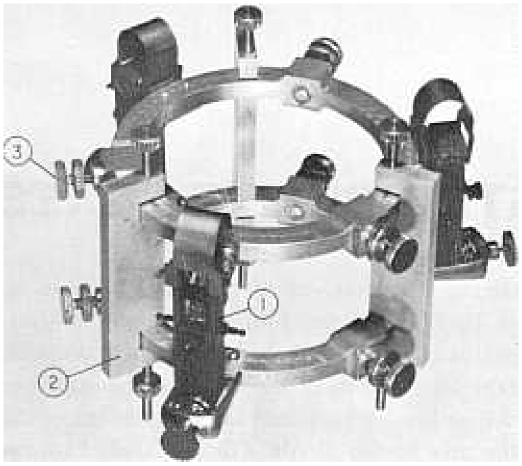
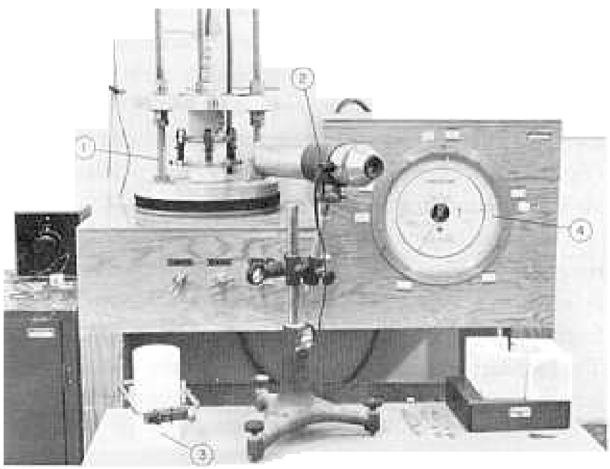


***Figure 1.*—Paddle-type plaster mixer for mixing plaster-celite.**



① Tuckerman optical strain gage
② removable spacer
③ set screw

Figure 2.—Optical strain gage compressometer.



① testing machine
② collimator
③ lateral compressometer
④ manometer

Figure 3.—Compressed-air testing machine.

of these instruments and a collimator, the relative movement of the rings and thus the strain in the test specimen could be obtained within 2 microinches per inch.

The compressometer for measuring lateral strains (figure 3) was similar to that generally used for making Poisson's ratio tests on 3- by 6-inch concrete specimens. Like the longitudinal compressometer, a Tuckerman gage was attached to the lateral compressometer for obtaining strain indications.

Loading of the plaster-celite test cylinders was done in a small testing machine, operated by compressed air. The machine was constructed so that concentric loads would be applied to the ends of the cylinder. This was accomplished by supporting the bottom of the cylinder on a hydraulic cushion and by loading the top of the cylinder with compressed air. Active and reactive pressures produced by the air and water, respectively, were transmitted through rubber membranes to the ends of the specimen. Air pressure applied to a specimen during a test was indicated by a dial-type manometer (figure 3).

The testing machine was mounted on a turntable so that when using the longitudinal compressometer, each Tuckerman gage in turn could be correctly positioned before the collimator.

The mix proportions by weight and physical properties of the plaster-celite materials used to construct the Glen Canyon and Morrow Point models were:

Glen Canyon Model

Dam

gaging plaster	1.00 part
molding plaster	3.00 parts
celite	1.00 part
water	4.80 parts
E	485×10^3 psi
μ (Poisson's ratio)	0.18

Foundation and Abutments

gaging plaster	1.00 part
molding plaster	3.00 parts
celite	5.20 parts
water	17.0 parts
E	80×10^3 psi
μ	0.20

Morrow Point Model

Dam

gypsum cement plaster (hydrocal)	.70 parts
celite	1.00 part
water	3.65 parts
E	242×10^3 psi
μ	0.18

Foundation and Abutments

gypsum cement plaster	0.98 part
celite	1.00 part
water	2.90 parts
E	150×10^3 psi
μ	0.16

As indicated in the preceding tabulations, the ratio, E (model dam) to E (model foundation) was approximately 6 to 1 for the Glen Canyon model and 1.6 to 1 for the Morrow Point model. These ratios correspond to the following concrete-to-rock ratios which were included in the design data for the models: 3×10^6 psi to 0.50×10^6 psi and 4×10^6 psi to 2.5×10^6 psi, respectively.

Typical stress-strain curves for plaster-celite used in the Glen Canyon model dam are shown in figure 4. Similar curves were obtained for the materials used to contruct the Morrow Point model.

In addition to moduli of elasticity and Poisson's ratio tests, measurements were made to find out whether the model materials were subjected to drying shrinkage. This information was obtained by measuring changes in length during the drying period of 4- by 4- by 30-inch plaster-celite specimens. These tests indicated that drying of plaster-celite produced an expansion rather than a shrinkage. For the Glen Canyon model the average value of this expansion for the foundation material was 34 microinches per inch, and for the model dam was 153 microinches per inch.

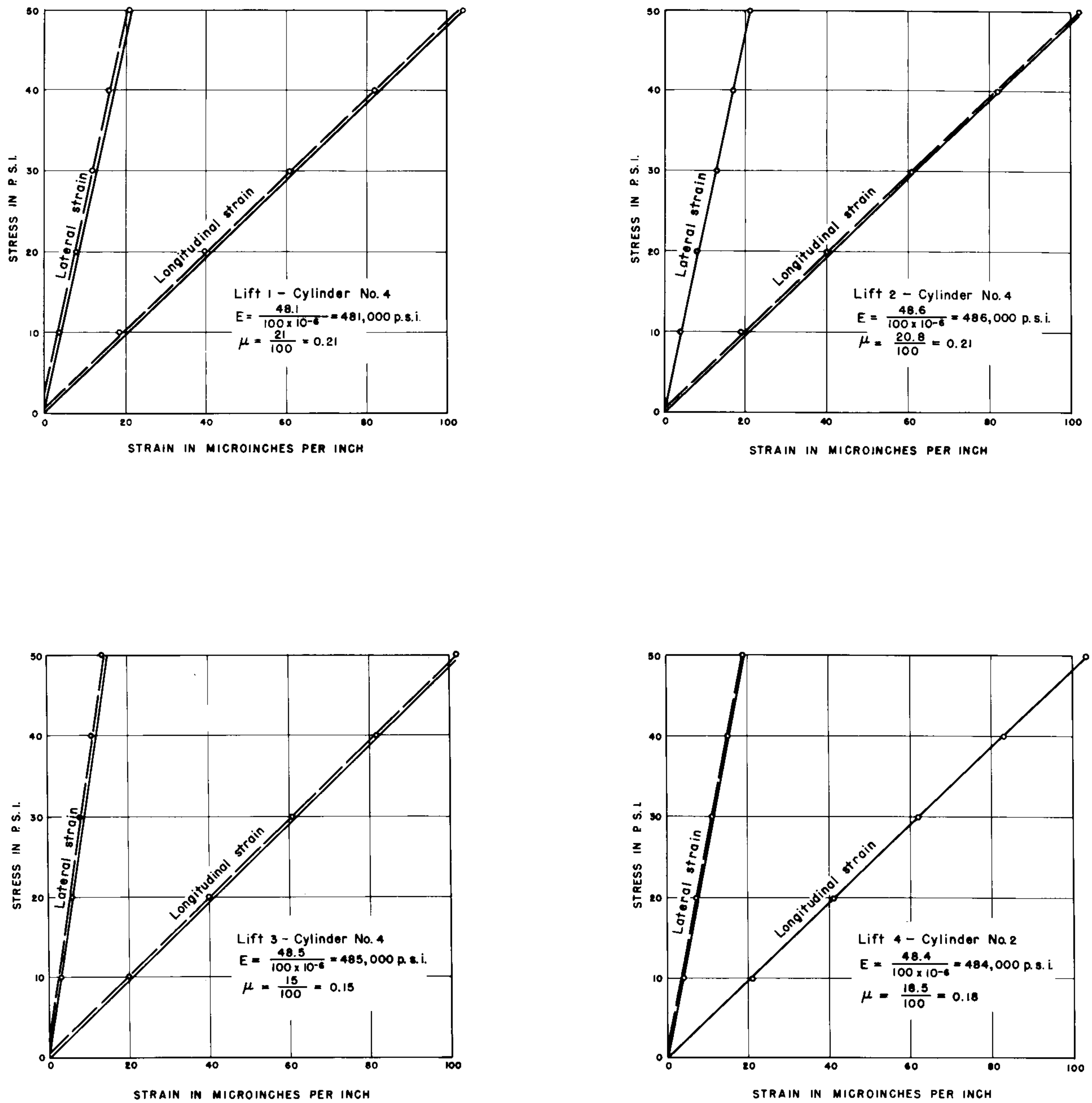


Figure 4.—**Typical results of physical property tests of material in model dam—Glen Canyon model.**

MODEL CONSTRUCTION

Three methods have been used to construct models of a mass concrete dam. The first is to cast the entire model as a unit and, when dry, to shape the dam and abutments with power routing equipment and hand tools. This procedure has been generally followed by LNEC for small plaster-celite models (model dam about 12 to 15 inches in height).

The second method, and the one employed by ISMES for large concrete-pumice models, is to cast the model as a unit, forming both the dam and the abutments to final shape. This method has been used by ISMES to prepare a 25-foot-high model of Vaiont Dam.

The third method for constructing models of dams is the one employed by the Bureau of Reclamation. It involves three operations: constructing the foundation and abutments to the approximate shape of the damsite, shaping of the abutments and keyways by means of hand tools, and, finally, building the model dam. With regard to the last step, the model dam has been either cast in place or cast as a unit and cemented in place.

Two schemes have been employed by the Bureau of Reclamation for constructing the foundation and abutments for structural models of dams. The first of these was developed during the preparation of the Hoover Dam model and was used until about 5 years ago on all models built by the Bureau of Reclamation. Using this scheme, the abutment and foundation materials were cast in 3-inch layers. For the model of Glen Canyon Dam, 23 such layers were needed to prepare the foundation and canyon walls (figure 5). Since 10 days were required to place and dry each layer, it can readily be seen that this method of construction is time-consuming. To ensure bond between the adjacent layers, the upper surface of each layer was keyed and painted first with two coats of orange shellac, and then with one coat of waterproof varnish.

The second scheme, which was employed by the Bureau of Reclamation for constructing the foundation and canyon walls for the Morrow Point model, includes the use of precast plaster-celite blocks 24 inches long, 12 inches wide, and 6 inches high (figure

***Figure 5.*—Model construction by the layer method—Glen Canyon model.**

***Figure 6.*—Model construction by the block method—Morrow Point model.**

6). The block-construction method was first employed at the University of California for construction of a model of an arch and buttress dam proposed as an alternate design for Oroville Dam [10].

Before beginning construction of the Morrow Point model, all blocks to be used in the model were cast in metal forms, dried at about 100 to 110° F., and then painted with a thin coat of "Araldite," an epoxy adhesive. The foundation and abutments were prepared by joining one block to another by means of a mortar consisting of a mixture of Araldite and celite. In this work it was important that each joint be subjected to a constant pressure until the mortar had set. Following placement of all blocks, the abutments including the keyways were cut to shape by means of hand tools (figure 7). The time for constructing the model canyon

Figure 7.—**Shaping abutments and foundation—Morrow Point model.**

by the block method was about one-quarter of that required for the layer method.

For the Glen Canyon and Morrow Point models, the dam was cast to its final shape. The Glen Canyon Dam model was cast in place by using separate wooden forms for each face of the model dam (figure 8).

This procedure, however, was not followed for the model of Morrow Point Dam. Instead, a carefully made wooden model of the dam (figure 9) was used to fabricate a plaster split mold in which the model dam was cast. By means of this technique, it was possible to prepare as many models of the dam as was necessary to obtain one which was free from surface imperfections. In addition to fabrication of the mold, the wooden model was also employed for checking the ex-

Figure 8. **-Upstream and lower sections of downstream form in place—Glen Canyon model.**

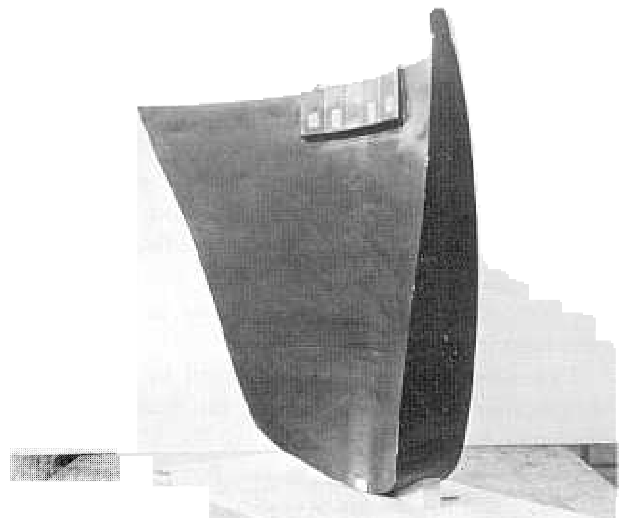


Figure 9.—**Wooden model of Morrow Point Dam.**

cavation of the keyways and for preparing the mercury loading bag reaction frame. The upstream and downstream forms for the model of Glen Canyon Dam, as well as the wooden replica of the Morrow Point model, were fabricated from sugar pine planks.

The Morrow Point model as originally constructed was a true representation of the prototype including the spillway structure (figure 10). The dam assumed for the trial-load analysis had the same shape as the prototype except that it did not include the spillway structure; that is, it did not include the spillway openings and the enlarged crown above elevation 7100. To

Figure 10.—Model of Morrow Point Dam in place.

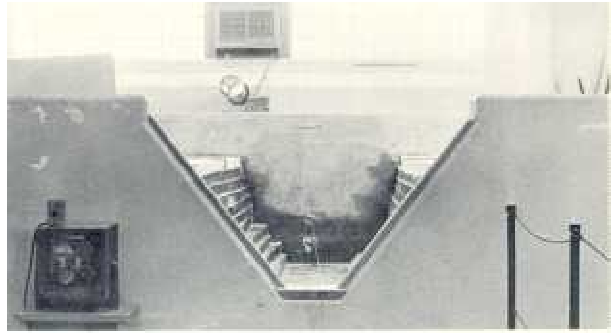


Figure 11. ·Model test pit.

obtain information on local stresses near the spillway, as well as stresses which could be compared to the computed stress values, tests were made on models with and without the spillway.

Glen Canyon and Morrow Point models were constructed in the same reinforced concrete test pit (figure 11), which had the following overall dimensions: length, 13 feet 8 inches; depth, 8 feet 2 inches; and height, 7 feet 4 inches. To provide rigid boundaries where the plaster-celite abutment material joined the sides of the pit, the side walls were constructed with a 12-inch minimum thickness. The front and the back walls of the pit were 10 and 8 inches thick, respectively. Since it was determined that the reactive forces produced by the mercury loading would cause wall deflections which could alter the model deflection measurements, the upstream boundary of each model was separated from the back wall.

The model test pit was located in a room where the air temperature could be controlled.

329–437 O—69——3

MODEL LOADING

Mathematical analyses of mass concrete arch dams usually take into account four conditions: water pressure, concrete weight and temperature, and dynamic loads produced by earthquakes. These are sometimes referred to as live, dead, and transient loads, respectively. In general, structural models of dams are only analyzed for live loads. However, attempts have been made to obtain dead load stresses by means of structural models at the University of California [10], LNEC [11], and ISMES [12]. The last two organizations named have also made dynamic tests on models by exciting model dams with either mechanical or magnetic-type shakers [13].

Live loads have been applied to models by means of hydraulic jacks or mercury. The jacking method, which was developed at ISMES for the cement-pumice models, has two drawbacks. First, jacks do not produce a true hydrostatic loading and, second, they create local stresses on the upstream face, with the result that adequate surface strains cannot be obtained on this portion of the model.

Jack loads are applied to a model through metal shoes. The bearing surface of each shoe is shaped to the same curvature as the area of the upstream face to be loaded by a shoe. So that the same fluid pressure can be applied to each jack for a simulated triangular loading, the cylinders of the jacks used for loading the lower portions of the model are fabricated with a larger internal diameter than those used near the top.

The simplest way to apply live loads to a structural model of a dam is by means of mercury. This is usually done by forcing mercury into a rubber bag (figure 12) in contact with the upstream face.

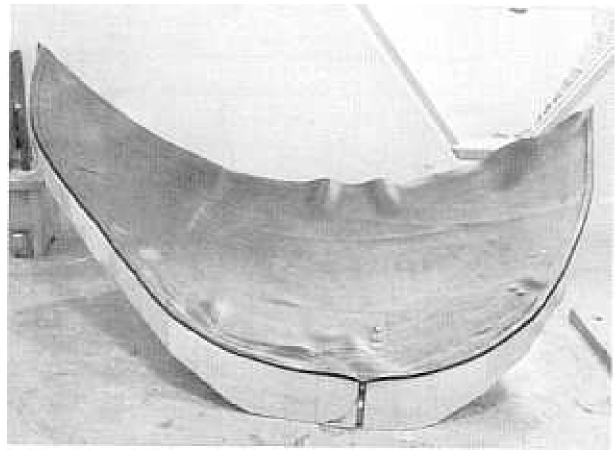


Figure 12.—**Mercury loading bag—Glen Canyon model.**

At LNEC the pressure required to do this was produced by raising the mercury reservoir tank by means of a hoist. For the Glen Canyon and Morrow Point models the required head was developed by pumping water into the mercury reservoir tank (figure 13).

Initially, for the Glen Canyon model, mercury head was produced by utilizing the available pressure head in the water mains. This was not satisfactory since the water from this source cooled the mercury supply which, in turn, produced a temperature gradient in the model dam. To ensure that the mercury supply would be at the approximate temperature of the model, the water used to displace the mercury in the tank was stored in a second tank placed near the model pit. Water pressure necessary to raise the mercury in the bag was produced by a small centrifugal pump.

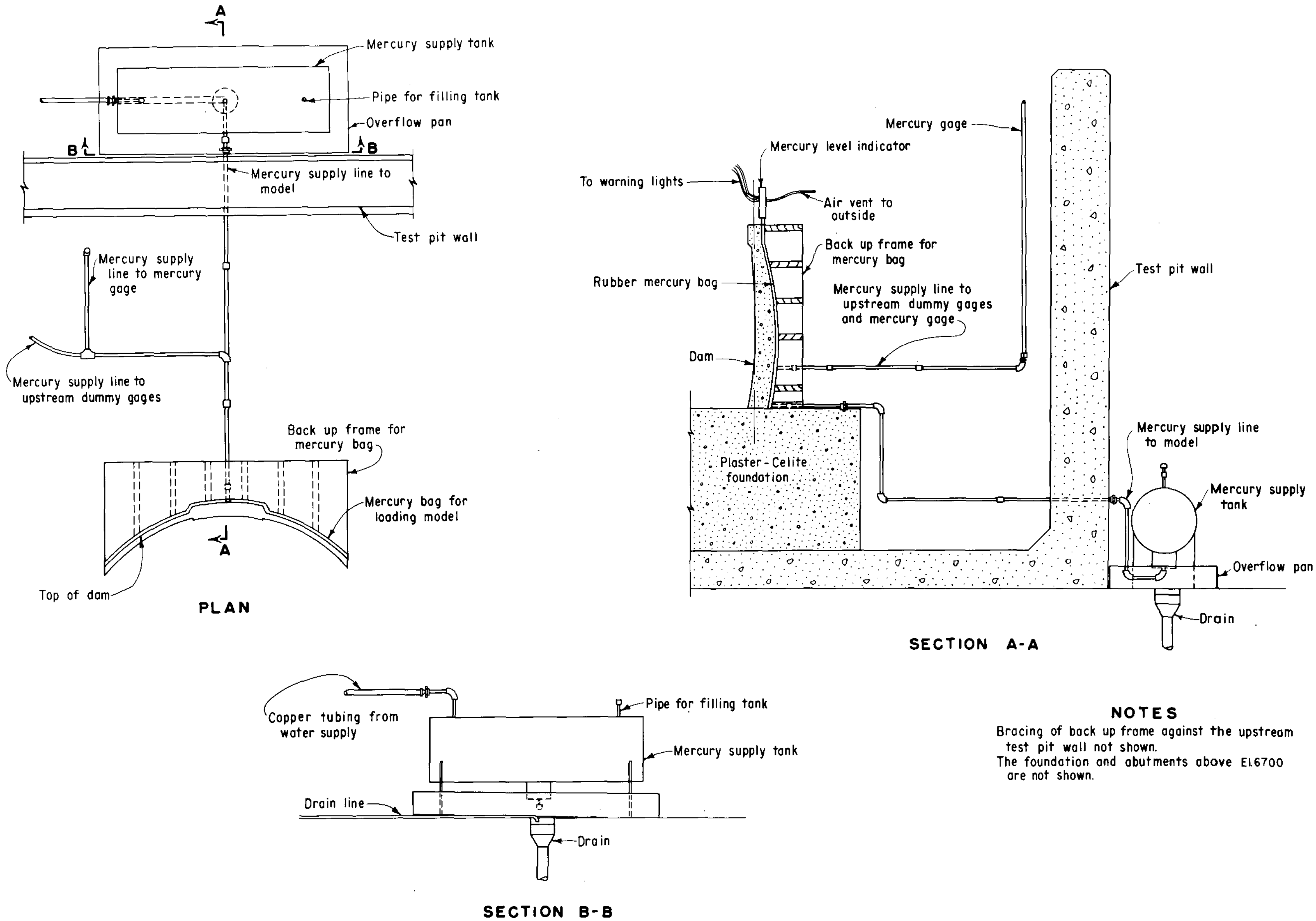


***Figure 13.*—Mercury supply tank and piping.**

MODEL TESTING

During the Glen Canyon and Morrow Point model tests, surface strains were measured on both faces of the model and radial and tangential deflections were measured at the downstream face. These are the usual measurements made during an analysis of a structural model of a concrete arch dam. In addition to these two types of measurements, techniques have also been developed for measuring rotations [4] for static loadings, and transient strains for dynamic loadings.

Analyses of concrete arch dams by the trial-load method usually include the computation of radial and tangential deflections and of principal stresses on the upstream and downstream faces at locations where continuity is established between the arch and cantilever elements. When a complete trial-load analysis is made, live, dead, and earthquake loadings, temperature gradients, and abutment deformations are taken into account. For modern arch dams, the deflections and stresses produced by temperature gradients usually exceed those produced by the other conditions mentioned. Thus, it can be seen that model tests made only for hydrostatic loadings do not furnish all the information needed to design a dam. Even so, if properly done, structural model tests do provide sufficient information to determine whether the analytical method used for designing a concrete arch dam is adequate. This determination is made by comparing model deflections and stresses with those computed by a trial-load analysis for hydrostatic loading only.

As mentioned, deflection measurements on model dams are made in radial and tangential directions from points on the downstream face (figures 14 and 15). In special model tests, vertical deflections, changes in chord length, and foundation deformations have also been determined.

For the Glen Canyon and Morrow Point models, deflections were measured by means of dial-type mechanical gages (figure 16), which indicate deformations to a precision of 0.0001 of an inch. So as not to cause extraneous movements of the model, it was important that only those gages be used which will produce a minimum force on the model. It was important, also, that the support device for each gage be attached to a reference structure which will not move throughout the duration of a test.

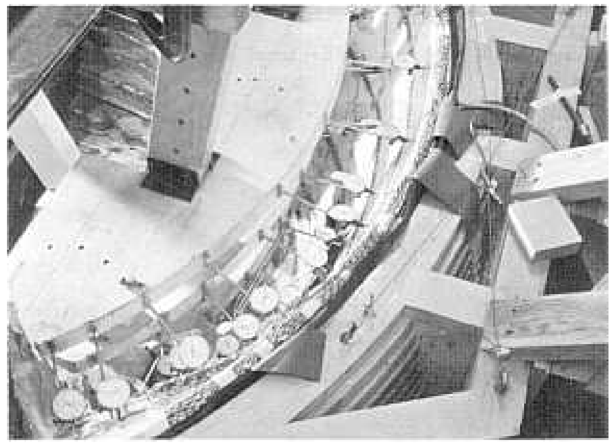


Figure 14.—**Set-up for radial deflection measurements—Glen Canyon model.**

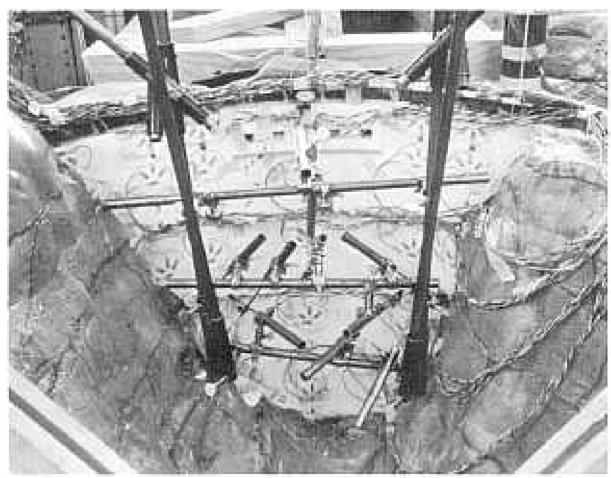


Figure 15.—**Set-up for radial and tangential deflection measurements—Morrow Point model.**

To provide an adequate bearing surface for each gage, a deflection button (figure 17) was attached to the model at each point of measurement. The button was made of three components: a small polished

Figure 16.—**Dial gages used for measuring model deflections.**

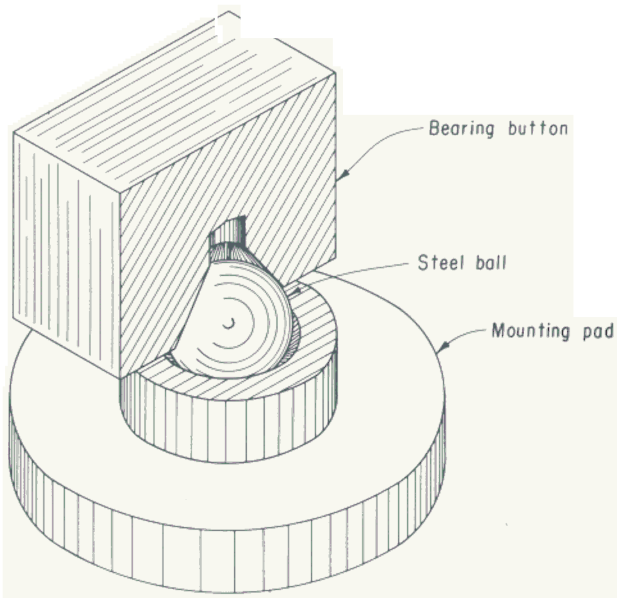


Figure 17.—Button used for measuring model deflections.

brass cube, a steel ball, and a disc-shaped mounting pad, which was secured to the model by nitrocellulose cement. The ball was fastened to the pad and cube by means of low-melting-point solder. Thus, it was possible with the button in place on the model to adjust the position of the cube by heating it with a small soldering iron. For most model tests, each cube was oriented so that its coordinate axes were in radial, tangential, and vertical directions, respectively.

Except for the cement-pumice models constructed by ISMES, model strains are currently being measured by means of bonded resistance wire (or foil) strain gages. At ISMES, tensometers and vibrating wire gages have been employed for making strain measurements.

To determine the principal stresses for one surface point on a model, a minimum of three strain measurements at that point is required. However, for Bureau of Reclamation model studies, a four-strain gage rosette is generally used (figure 18); thus, one redundant strain measurement is obtained. This additional measurement provides a means for detecting faulty gages and for obtaining a least squares adjustment of the measured data (see Bulletin 6 [3]).

Axes chosen for the 4-gage rosette were horizontal (H), 45° (D), 90° (V) and 135° (d), where the angles to the D-, V-, and d-axes were measured counter-clockwise from the positive extension of the H-axis. Each rosette was formed by mounting ½- or ¼-inch foil-bonded resistance strain gages (SR–4 type) on the plaster-celite model surfaces in the array shown in figure 18.

Foil strain gages were attached to a plaster-celite model by means of nitrocellulose cement. The rosette area was treated with a precoat cement before the gages were cemented in place.

To ensure that the method adopted for mounting the bonded-type strain gages would give reliable strain indications, tests using these gages were made on 3- by 6-inch plaster-celite cylinders. These tests were performed by checking the average longitudinal strains indicated by the three bonded strain gages mounted axially 120° apart on the cylinder against the average strains measured by the longitudinal compressometer. Each cylinder was tested in the compressed air testing machine for pressures ranging from 0 to 50 psi.

When measuring strains on plaster-celite models of dams by means of bonded strain gages (figures 19 and 20), certain problems arise which are not encountered

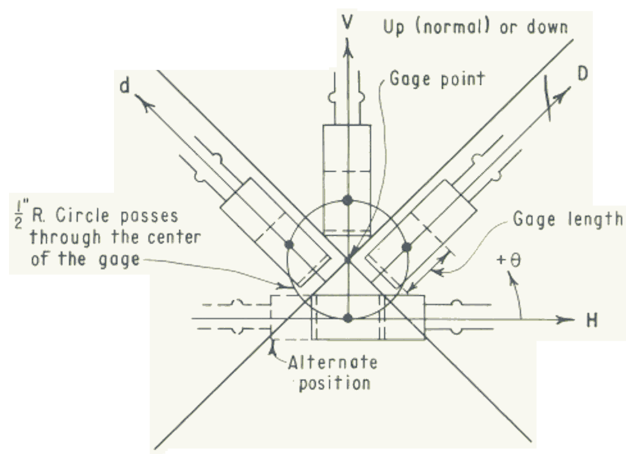


Figure 18.—**Orientation of strain gages in rosette.**

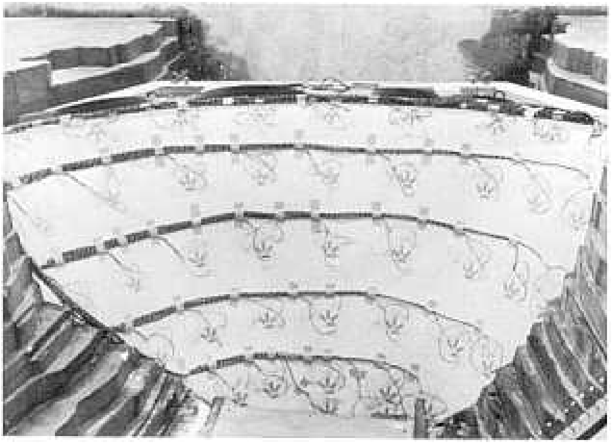


Figure 19.—**Strain gages on downstream face—Glen Canyon model.**

Figure 20.—**Strain gages on upstream face—Morrow Point model.**

in the measurement of strains on other materials. Some of these problems are:

1. Since plaster-celite is a poor conductor of heat, gage drift may take place unless a separate dummy gage is used for each active gage.

2. To obtain satisfactory results, extra care must be taken when mounting the gages to make certain that no air bubbles are entrapped in the cement.

3. Errors in strain readings for gages mounted on the upstream face of the model dam can be caused by sliding of the mercury bag along the face, by normal pressure produced on a gage by the mercury loading, and by a difference in model and mercury temperatures. To reduce errors in measured strains resulting from the effects of the application of load to the upstream face, the following measures were taken:

   a. Two sheets of pliable plastic material were inserted between the mercury bag and the model.

   b. Dummy strain gages were mounted on plaster-celite blocks which were subjected to the same mercury temperatures and pressures as the active gages. To accomplish this, one block with several dummy gages attached was furnished for each elevation on the model where strain measurements were taken. The blocks were stacked vertically in a frame and were loaded in the same manner as the model dam.

Dummy strain gages for the strain gages mounted on the downstream face were cemented to a plaster-celite cylinder which was placed near the dam.

DATA REDUCTION

As stated, one of the aims of the model studies of Glen Canyon and Morrow Point Dams was to obtain comparisons between experimental and computed data. Since the computed data available for these comparisons were prototype stresses and deflections, it was necessary to convert model measurements to similar quantities. This was done in two steps: first, principal stresses for each model were determined from the measured strains, and second, model stresses and deflections were converted to like quantities for the prototype.

The relations for calculating stresses from strain measurements may be found in texts on the mathematical theory of elasticity. Magnitudes and directions of the principal stresses can be obtained by graphical or numerical solutions. Two graphical solutions used for principal stress computations are Mohr's [14] and Land's [15] circles. A detailed explanation of a numerical method for making strain-stress computations is given in Chapter VI, Bulletin 6 [3].

Converting model stresses and deflections to corresponding prototype values was done by means of the following relations:

$$\sigma_p = nk\sigma_m$$

$$\delta_p = \frac{n^2 E_m}{k E_p} \delta_m$$

where

σ_p=prototype stress (psi);

σ_m=model stress (psi);

n=scalar ratio, prototype to model. Glen Canyon model, n=240:1; Morrow Point model, n=180:1;

k=hydrostatic pressure ratio, model to prototype. k=13.6, since mercury loadings were used for the Glen Canyon and Morrow Point models;

δ_p=prototype deflection (in.);

δ_m=model deflection (in.);

E_p=modulus of elasticity of prototype concrete. Glen Canyon Dam concrete, $E_p=3\times10^6$ psi; Morrow Point Dam concrete, $E_p=4\times10^6$ psi;

E_m=modulus of elasticity of material in model dam. Glen Canyon model dam, $E_m=485\times10^3$ psi; Morrow Point model dam, $E_m=242\times10^3$ psi.

Therefore, the equations for converting model stresses and deflections to like quantities for the prototypes are:

Glen Canyon Dam:

$$\sigma_p = 17.6\ \sigma_m$$
$$\delta_p = 685\ \delta_m$$

Morrow Point Dam:

$$\sigma_p = 13.2\ \sigma_m$$
$$\delta_p = 144\ \delta_m$$

TEST RESULTS—GLEN CANYON MODEL

Principal stresses and deflections obtained from the Glen Canyon model tests are plotted in figures 21 through 24. These data were obtained for a mercury head corresponding to the normal water surface (elevation 3700). These figures also include stresses and deflections which were computed for the right half of the model dam.

Comparisons of principal stresses for the upstream face show satisfactory agreement between experimental and computed values. Except at the crest, the experimental stresses were slightly larger than the corresponding computed values. The maximum experimental tensile stress (+39 psi) occurred near the abutment intrados at elevation of 3695 (Point 1f). The maximum compressive stress (−774 psi) was obtained for Point 9d. The corresponding computed value for this location is −641 psi.

Better agreement between experimental and computed stresses was obtained for the upstream face than for the downstream face. High tensile stresses generally parallel to the abutment intrados line were obtained near the toe of the model dam. The maximum value was found to be +736 psi. The corresponding computed value is +262 psi. Maximum experimental compressive stresses also were found at the toe of the model dam. The largest value, which was obtained for Point 8b, was −871 psi.

Like the principal stresses, the model deflections were generally greater than the computed values. This was particularly true for the computed tangential deflections, which for most points of measurement were about one-half the experimental values.

The maximum radial deflection, measured at Point 9e on the model, was equal to 5.2 inches. In comparison, the computed radial deflection at this point is 3.7 inches.

Maximum tangential deflections occurred near the contact between the dam and its foundation. The largest tangential deflection (3.8 inches) was measured at Point 5c. At this point, the computed tangential deflection was less than one-half of this amount, or 1.5 inches.

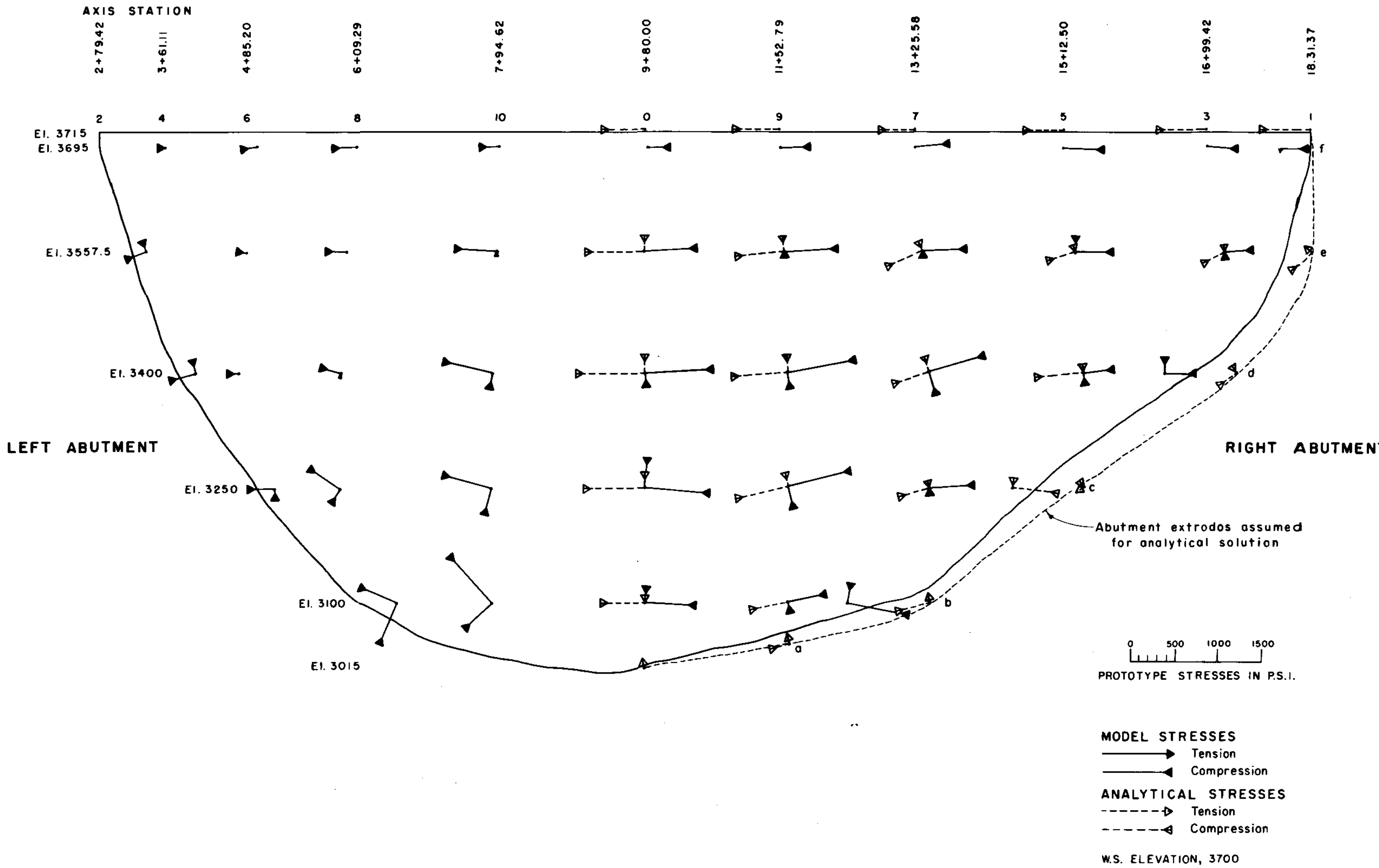


Figure 21.—**Principal stresses, upstream face—Glen Canyon model.**

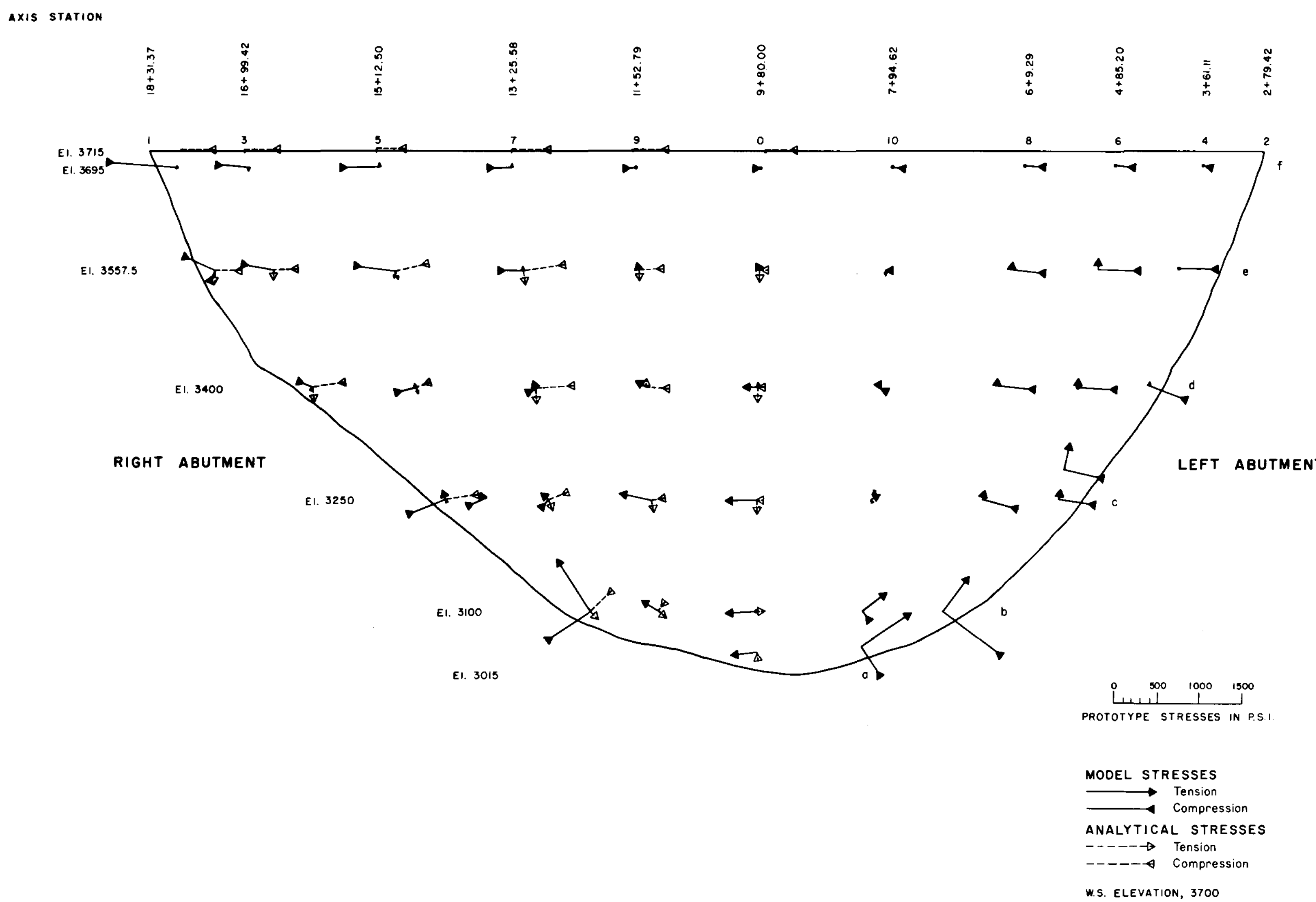


Figure 22.—**Principal stresses, downstream face—Glen Canyon model.**

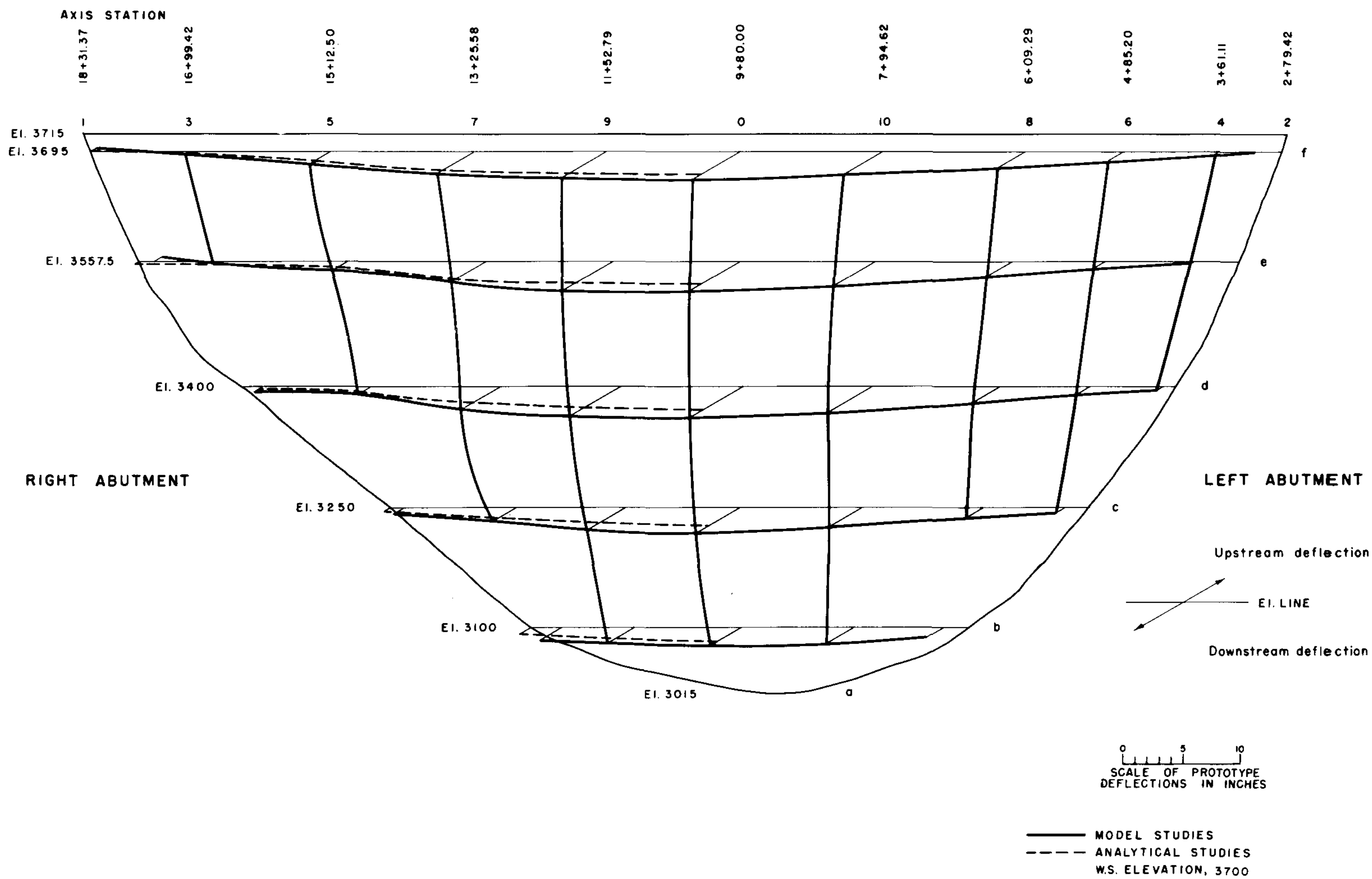


Figure 23.—**Radial deflections—Glen Canyon model.**

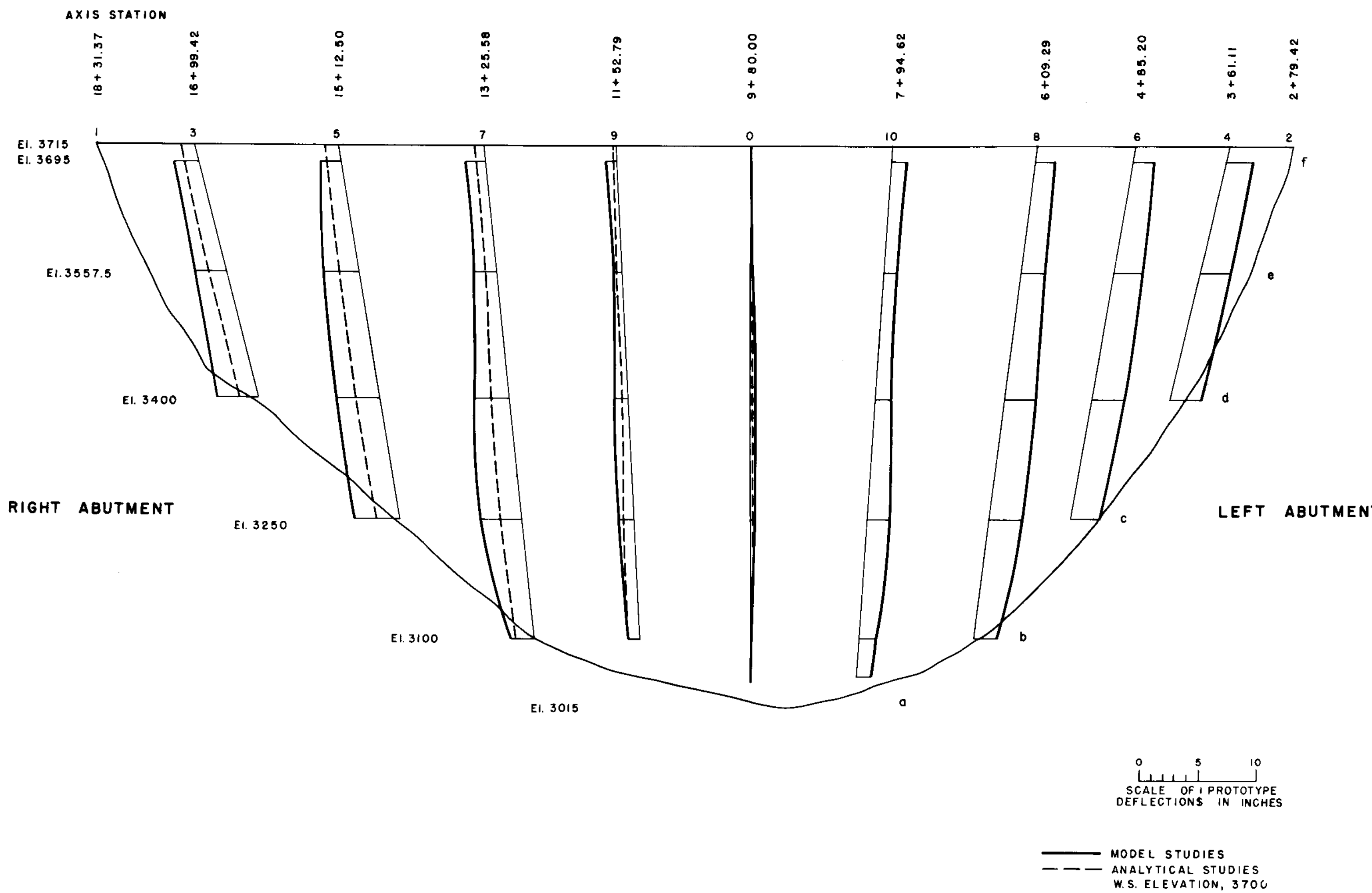


Figure 24.—Tangential deflections—Glen Canyon model.

TEST RESULTS—MORROW POINT MODEL

As noted, the spillway for Morrow Point Dam is located midway between the abutments near the crest. The spillway consists of four openings. To reduce local concrete stresses produced by these openings, the thicknesses of the arches above elevation 7100 were increased as shown in figure 10.

Structural model investigations of the dam included tests with and without the spillway. Since the model dam was cast to represent the prototype, tests of the model with the spillway were made first. Following completion of this study, the portions of the spillway structure which extended beyond the faces of the model dam were removed and plaster-celite plugs having the same physical properties as the model dam were fitted and cemented into the openings. These two alterations were made to provide a model having the same geometrical shape as the structure for which the computed stresses and deflections were obtained.

Comparisons of Morrow Point model stresses and deflections with computed values are shown in figures 25 through 28. Since the dam is essentially symmetrical, computed data were only obtained for the left half of the dam. However, for purpose of comparison, stresses and deflections computed on lines 2, 4, and 6 were also plotted at similar points along lines 1, 3, and 5, respectively.

Except near the heel and toe, the principal stresses obtained from measurements on the model agree satisfactorily with those computed by the trial-load method of analysis. At these locations the stresses found by the two methods do not have the same sign. For example, the model stresses at the heel (Point 0a) indicate a compressive stress field, whereas the computed stresses at the foundation contact between lines 5 and 6 indicate a tensile stress field.

The maximum live load compressive stresses obtained from the model data are −978 psi (downstream face, Point 4c) and −806 psi (upstream face, Point 0c) for the same loading conditions. The maximum tensile stresses are +255 psi (downstream face, Point 0a) and +40 psi (upstream face, Point 3c).

Tests of the model with and without the spillway structure indicate that local stresses produced by the openings and thickening of the top arches at the crown were small. The largest stress change obtained for the two tests was about 100 psi at Point 5j, upstream face. The stresses obtained for models with and without the spillway were −287 and −179 psi, respectively.

Except for the top arches, comparisons of the model and computed deflections are satisfactory. As obtained for the Glen Canyon model study, model deflections were generally larger than the computed values.

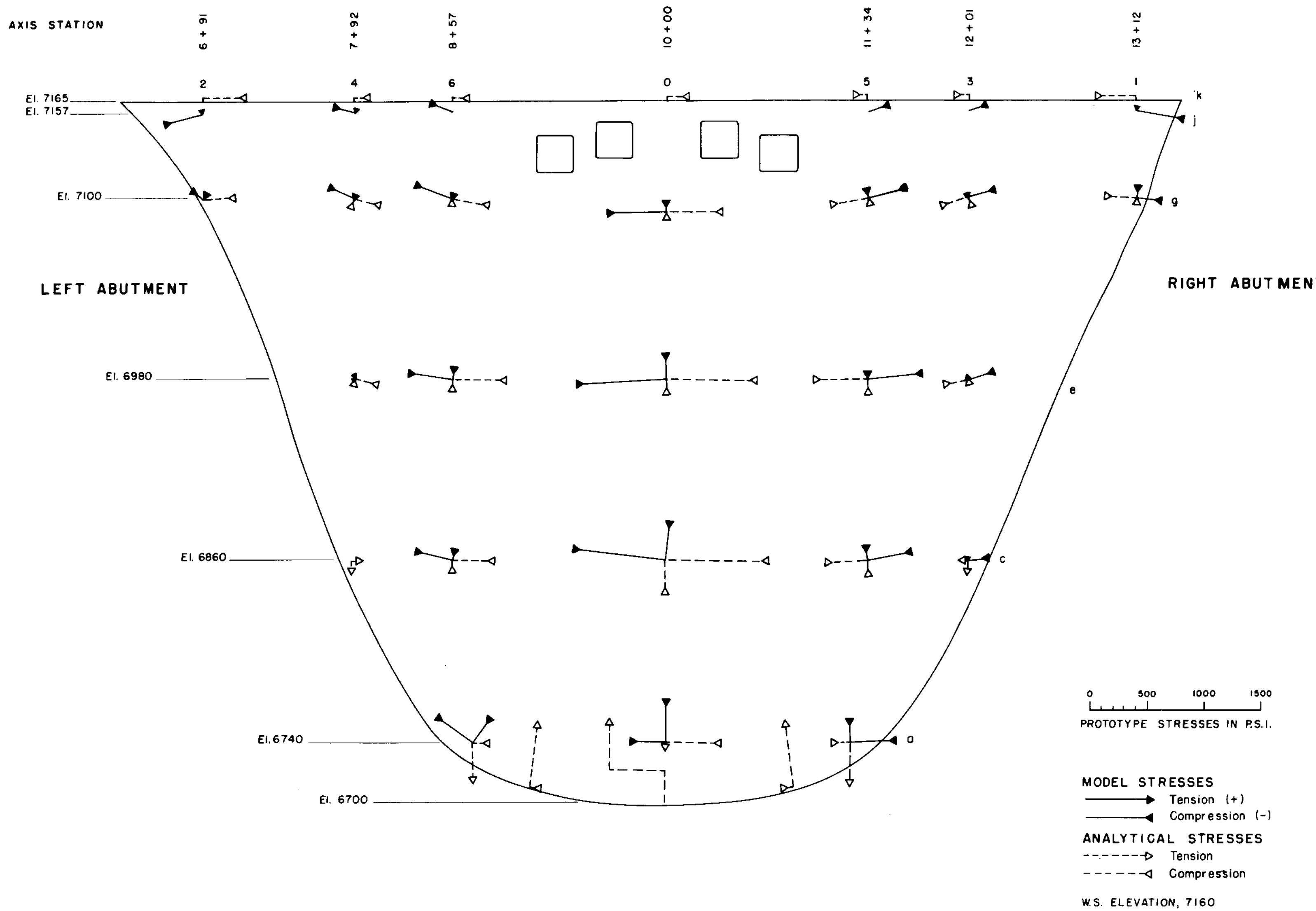


***Figure 25.*—Principal stresses, upstream face—Morrow Point model.**

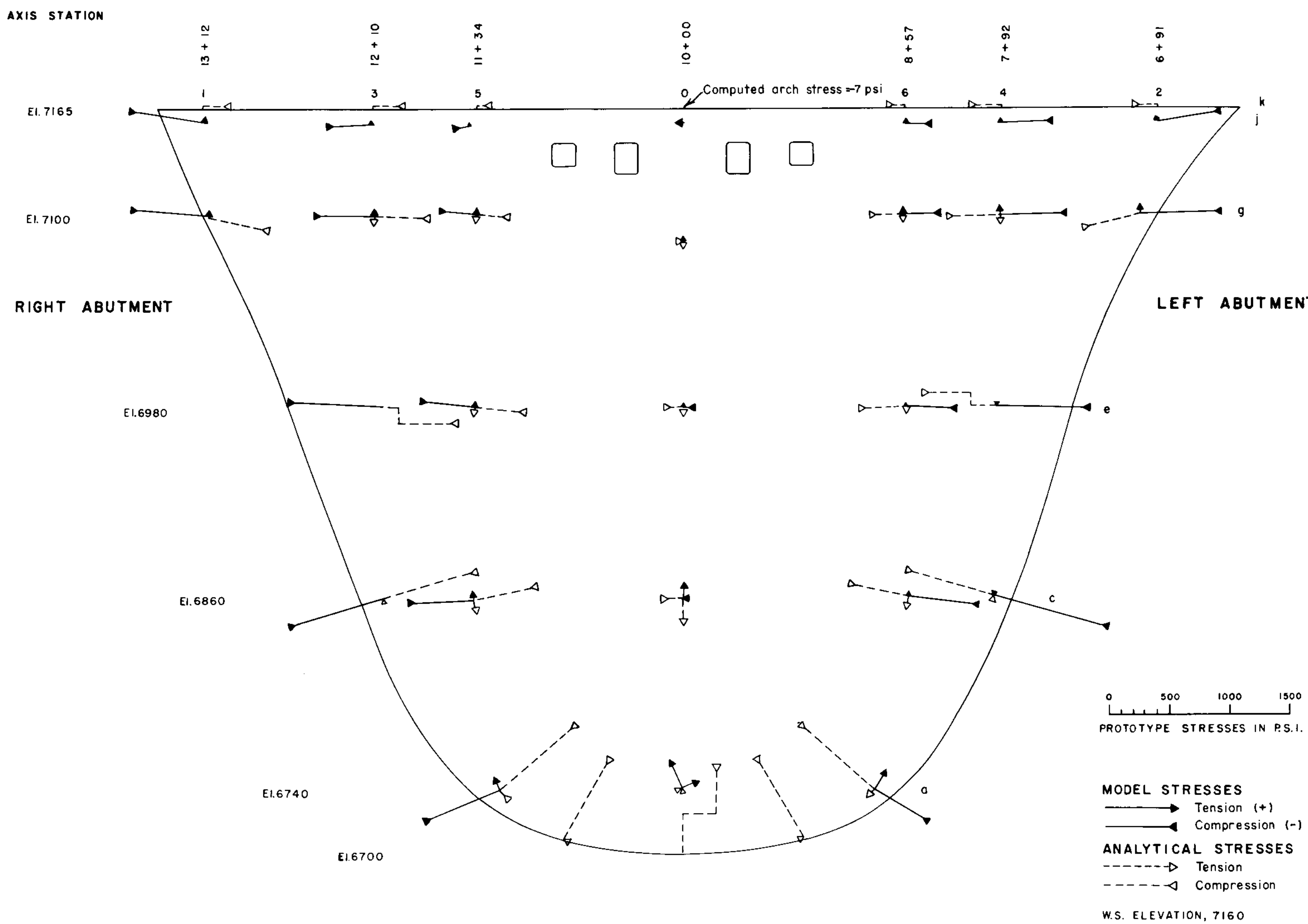


Figure 26.—Principal stresses, downstream face—Morrow Point model.

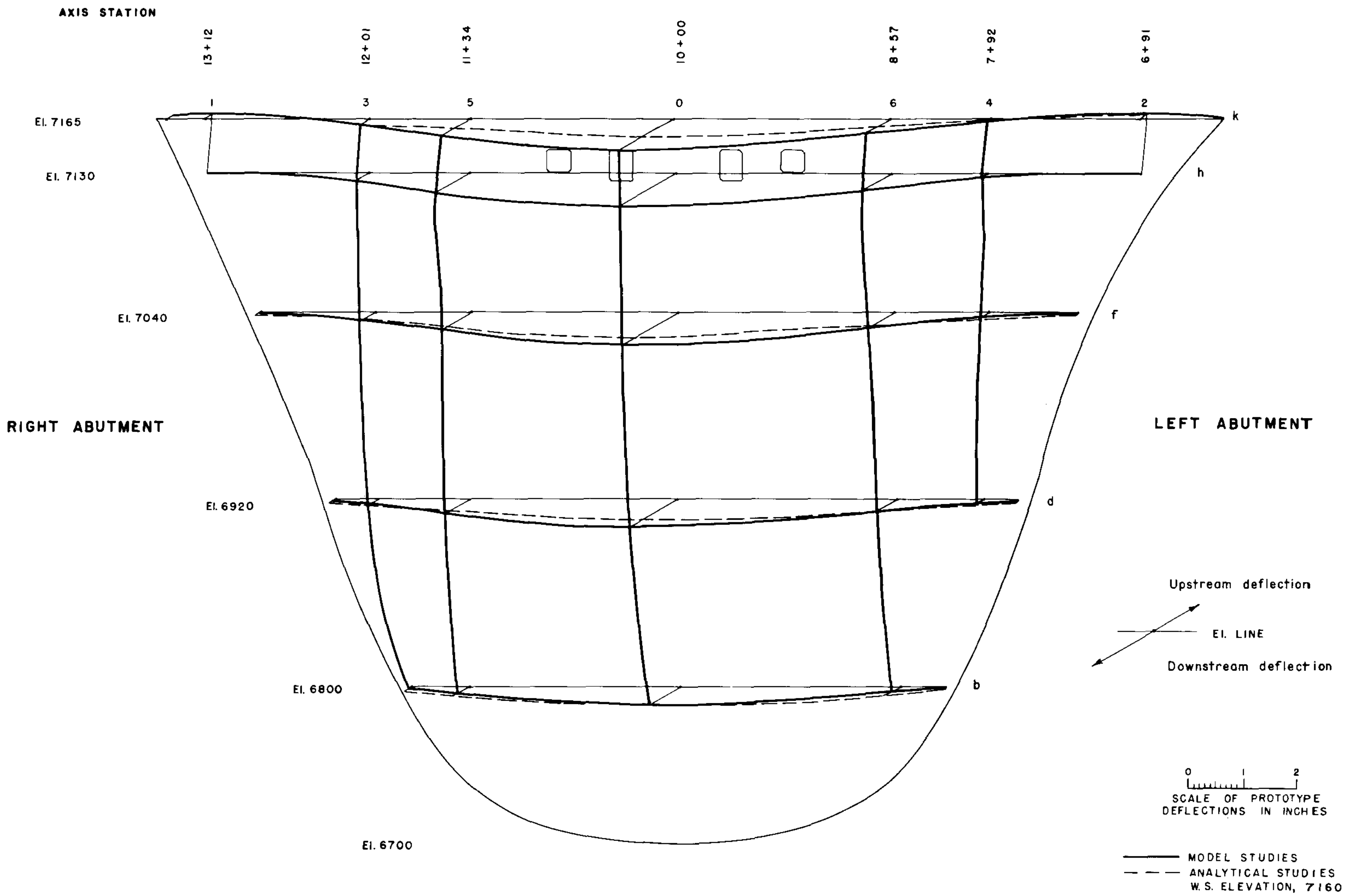


Figure 27.—Radial deflections—Morrow Point model.

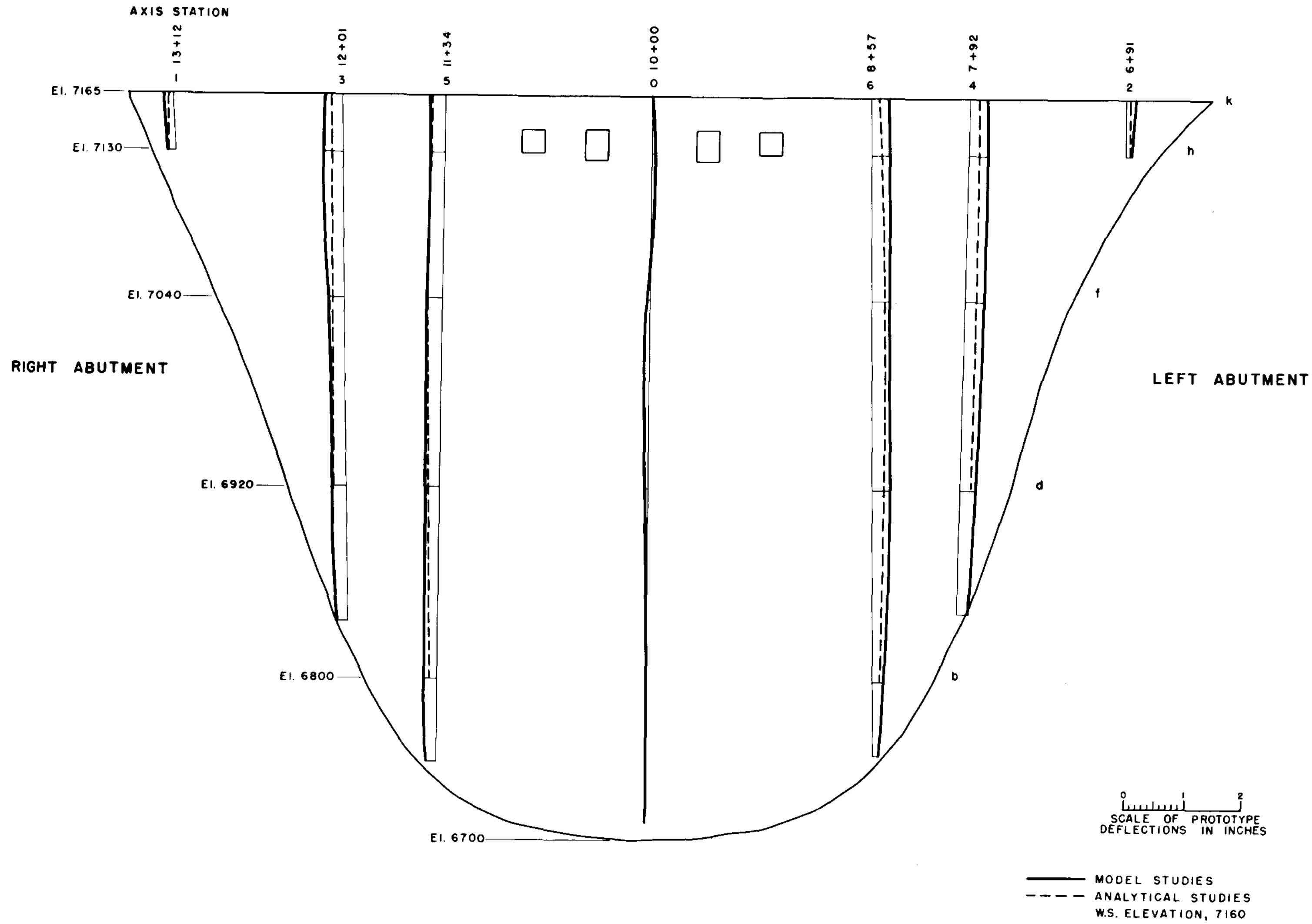


Figure 28.—Tangential deflections—Morrow Point model.

CONCLUSIONS

1. A model dam having surfaces free from visible holes can be produced by mixing plaster-celite under a partial vacuum.

2. Model abutments can be built more efficiently by the block method than by the layer method. Casting of the canyon walls in layers is not satisfactory unless the shellac and varnish coating on a dried layer remains watertight during the period required to place and dry the layer above it.

3. Casting of a model dam as a unit and cementing it in place in the keyways produces a more satisfactory model than when the model dam is cast in place.

4. Hydrostatic loadings can be applied satisfactorily to the upstream face of a model dam by mercury contained in a rubber bag. If strain measurements are to be made on the upstream face, means should be provided for ensuring that the mercury is at the same temperature as the model.

5. The results of model and specimen tests indicate that bonded-foil type resistance strain gages will give reliable strain indications for plaster-celite surfaces if the surfaces do not contain imperfections such as visible holes.

6. To obtain satisfactory results, model testing should be performed in a room where the air temperature can be controlled within 2° F. of the mean room temperature. This is particularly important when bonded-wire gages are used to obtain strain measurements on the surface of a model dam.

7. At nearly all measurement points, model deflections were greater than the corresponding computed deflections. The test results indicate that the larger deflections obtained for the model dam may have resulted from model abutment deformations greater than those computed by the trial-load analysis of the model.

8. Good agreement was obtained between model and computed principal stresses except near the heel and toe of the Morrow Point model.

9. Test results on Morrow Point models with and without the spillway indicate that the spillway openings and enlargement did not cause an appreciable change in the principal stresses near the crest of the dam.

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Other reports on structural model tests for mass concrete dams may be found in publications by R.I.L.E.M. and by the Congress on Large Dams.

*Reunion Internationale des Laboratories D'Essais et de Recherches sur les Materiaux et les Constructions.

ABSTRACT

This report outlines techniques used by the Bureau of Reclamation in making structural analyses of Glen Canyon and Morrow Point concrete arch dams by means of models. Included in the report are: a short history of model testing for concrete dams, preparation of model materials, model construction techniques, and loading and testing methods. Included also are comparisons of model stresses and deflections with similar quantities computed by the trial-load method. Model testing techniques used by the Bureau of Reclamation are compared with those developed in Portugal at the Laboratorio Nacional de Engenharia Civil (LNEC) and in Italy at the Instituto Sperimentale Modelli e Structure (ISMES). The report has 15 references.

DESCRIPTORS— / structural analyses / *arch dams / concrete dams / models / *model tests / deflection / stress analysis / test procedures / *structural models / bibliographies / loads / trial-load method / dam design / safety factors / analogs / materials / mechanical properties / elasticity modulus / Poisson's ratio / plasters.

IDENTIFIERS— / Glen Canyon Dam / Morrow Point Dam, Colo.

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