ARCH-DAM INVESTIGATIONS ON MODELS
MADE OF ELASTIC MATERIALS

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Investigations conducted on models made of elastic materials make possible the evaluation of the strength of the subject structure, both by the method of permissible stresses, and from the aspects of limit-state design. The relatively small scale of the models simplifies test set-ups and allows design to be carried out in the laboratory, e.g., finding rational forms and designs of dams for the definite constructional conditions under consideration and establishing optimum program sequences for their construction, loading, and monolithization. These investigations also permit an assessment to be made of the effects on the static performance of a dam, which are produced by foundation-rock yielding and heterogeneity, diverse joints in the canyon sides, and many other factors which cannot, without difficulty, be evaluated by computation [1].

The investigation of the stressed state in arch dams, using models made out of elastic materials, is finding increasing favor, both in the USSR and abroad. This article sets forth some results of experiments which were carried out by the polarizational-optical method, at the Optico-Mechanical Institute (OMIN) of the B. E. Vedeneev All-Union Scientific-Research Institute of Hydraulic Engineering (VNIIG).

The tests were conducted in accordance with a specially developed method [2], characterized by the following essential features:

1. Models of the dams and the foundation were prepared by mechanical means, from epoxy resins of different rigidities which possess the property of "freezing deformations." This made it possible to model heterogeneous foundations, any major inclusions present, etc. As well as representing the dam itself, the model usually reproduced the riverbank massifs, extending laterally for a distance of five to ten arch-base widths from the abutments, to a depth of 30 to 50% of the dam height, and with upstream and downstream spreads of 50% of the arch span at crest level. To prevent "collapses" of the river banks during the test, the model was enclosed in a special box made from the same resin. The box dimensions and its wall thicknesses were published by special methodical tests.

2. Model loading was effected in a centrifuge. The centrifugal forces generated in the model (provided the centrifuge radius is sufficiently large compared to the model dimensions) are made equivalent to the gravitational or inertial forces, taken into account when analyzing for dead load and for seismic effects, respectively.

When modeling for dead load, deformations due to riverbank load were considered as having been completed before dam construction. For this, the deformations due to bank load only were first "frozen," then the dam model was glued into the deformed banks, followed by a repetition of "deformation freezing" [3] (the property of "deformation freezing" [4] is possessed by some high-molecular-weight polymers). When modeling the program sequence of dam construction, this process was repeated many times [5], or the investigations were conducted on several models which reproduced the main stages in the construction program [6].

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Fig. 1. Isochromatic pattern in the arches of Inguri Dam with a non-circular profile, under the action of hydrostatic pressure.

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in the tests, sometimes with different horizons. The investigation of the action of inertial seismic forces on the structure's body was carried out in the centrifuge, with the model turned to a position in the chamber which depended on whether modeling was concerned with longitudinal or transverse seisms, or the combined effect of seismic and gravitational forces [9].

3. For determining the stresses at model sections, the models were sawn into separate thin slices and investigated in a polarizing set-up (Fig. 1). In most investigations, the method of "successive slicing" was applied [5]. When processing measurement results, allowance was made for the fact that, at remote distances from the abutments, arch dam function as shell structures and hence assumptions were made which simplified stress computation procedures. At the abutment outline, the processing of measurement results was carried out without simplifications, in accordance with the usual functions for three-dimensional photoelasticity.

For each model, the investigations led to determinations of: (1) the magnitudes of arch and cantilever stresses at horizontal and vertical sections of the dam; (2) the magnitudes and directions of the principal stresses at the model faces; (3) the normal forces, transverse forces, and bending moments at the sections under consideration and, in particular, at the faces adjoining abutments; and (4) the magnitudes and directions of reaction forces at the dam spring lines.

The effect on dam performance of openings through its body, joint-notches or cracks, and other factors, was also studied in specially set-up experiments.

In collaboration with the design organization, the investigation results were subjected to analysis, and appropriate amendments were introduced into the dam construction program. The tests were repeated when necessary.

Presented below are the results of investigations carried out by the laboratory at the Optico-Mechanical Institute (OMIN) of the B.E. Vedeneev All-Union Scientific-Research Institute of Hydraulic Engineering (VNIIG), for the Inguri and other hydroelectric stations.

The arch dam for the Inguri hydroelectric station, 270 m high, is being constructed in a canyon whose sides are composed of rocks having different mechanical characteristics. The schematized picture of the geological conditions indicates three distinct zones in the canyon sides: (1) the lower (with a deformation modulus $E$ of 190 tons/cm$^2$), (2) the middle ($E = 80$ tons/cm$^2$), and (3) a weak region on the right-hand side, near the dam crest ($E = 20$ tons/cm$^2$).

During the first stages of design carried out in the laboratory, several alternatives for dam construction were tested, differing in regard to profile shape and concrete volume. The investigations were carried out by the polarization-optical method on six models made of photoelastic materials [3, 6]. As the result of these investigations, it was established that the maximum tensile cantilever stresses at the upstream face, caused by water pressure, diminish 20% with increase in profile curvature, but the reduction at the downstream face is only 8 to 10%; whereas arch stresses change insignificantly (the divergence of maximum stresses does not exceed 6 to 7%). It was also established that the heterogeneity of the dam foundation leads to a sharp change in its stressed condition. Comparison of the results obtained for one alternative type of dam construction, with homogeneous and heterogeneous formations of the canyon sides, respectively, showed that the unique geological formation causes overloading of the lower part of the dam, an increase in the irregularity of stress distribution along the dam shell thickness, and an increase in the magnitude of maximum stresses. Therefore, further investigations were directed toward finding a rational configuration for the dam arches. The alternative developed on the basis of the laboratory investigations has non-circular arches, described by three centers. In the proposed alternative for the dam, arch curvatures at the crown and the rise are slightly increased, and in the zones near the canyon sides, the adopted curvature is markedly less than in the corresponding alternative with circular arches (in the process, the dam concrete volume was reduced by approximately 200,000 m$^3$). The aperture angle of the circular portions with the increased curvature was adopted at the maximum value for arches at middle elevations and was reduced toward both the crest and the base of the dam. Variable central angles were adopted in view of the fact that the maximum irregularity in stress distribution along the dam shell thickness was observed to occur specifically in the middle arches of the dam.

Investigations were carried out on one alternative type of dam construction which employed non-circular arches (two models) and, for comparison, on a dam having circular arches (two models) for hydrostatic pressure and dead load. Some results of these investigations are presented in Fig. 2.

For arches of non-circular configuration the model investigations corroborated the reasoning which aimed at a reduction of the compressive stresses in the central zone and at obtaining a more uniform stress distribution across the shell thickness. The maximum tensile stresses in the arches and cantilevers, caused by the hydrostatic pressure,