AN ARCH DAM DESIGN METHOD FOR SEISMIC LOADINGS

by

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SYNOPSIS

The Bureau of Reclamation has been investigating for more than 35 years the dynamic response of dams and other structures to time-varying earthquake loadings. This paper outlines a method recently developed by that organization for computing the dynamic response of arch dams to these loadings. Included also in the paper are data on dynamic moduli of elasticity for mass concrete, structural damping for arch dams, and comparisons of measured and computed natural frequencies and mode shapes.

INTRODUCTION

Until recently, earthquake loadings were accounted for in the design of an arch dam by multiplying each element of mass in the dam by a constant value of acceleration acting in an upstream-downstream direction (1). For this type of loading to be valid the dam and its foundation would have to be rigid. Structural behavior measurements made on dams during the past 40 or more years have shown that arch dams are flexible rather than rigid. This observation is particularly true for the thin-arch double-curvature type dams used at the present time.

Engineers have been studying the dynamic response of structures to seismic forces since strong-motion ground vibrations were recorded during earthquakes. One of the first Bureau of Reclamation structures analyzed for time-dependent seismic forces was the Pit River Bridge, which crosses the reservoir impounded by Shasta Dam in California (2). About 8 years ago, methods based on the response-spectra concept were developed for computing the seismic stresses in arch dams (3 and 4).

Although engineers have known for some time how to solve the dynamic earthquake-loading problem for arch dams, electronic computers of sufficient capacity to process the arithmetic required in the step-by-step solution of the problem were not available. Such equipment has only been marketed for about 5 years.

The following is an outline of the analytical method presently being used by the Bureau of Reclamation to estimate earthquake and combined (earthquake plus static) stresses in arch dams. The method is based on structural dynamic theory. Ground vibrations applied to the dam boundary at the rock-concrete contact are time-history accelerations derived from strong-motion earthquake records. This paper also

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includes data on structural damping and dynamic moduli of elasticity for mass concrete. Comparisons of computed and experimental natural frequencies and mode shapes are given.

OUTLINE OF ANALYTICAL METHOD

The theory of structural dynamics used in the analysis of structures for earthquake loadings is summarized by Professor Clough in Chapter 12 of Reference 5. Following in general the procedures given in this chapter, the steps required in the solution of the earthquake loading problem for arch dams are:

1. Development of the maximum probable design earthquake for a damsite location
2. Computation of inertia effects and flexibility of the dam
3. Computation of natural frequencies and mode shapes
4. Computation of stresses produced by earthquake and combined loadings.

Since a dam is a critical structure, the design earthquake should be one which will produce the maximum probable ground vibrations at the damsite during the service life of the structure. Considered in estimating the maximum acceleration and frequency content of the design earthquake for a dam are: local and regional geology and seismicity, distance of local and regional faults from the damsite, the maximum probable earthquake which can occur along these faults, and the ground vibrations which will be generated at the damsite by this earthquake (6). Before reliable estimates can be made of the maximum probable earthquakes for dams, additional strong-motion data will have to be obtained.

To determine the inertia properties and flexibility (reciprocal of stiffness) of an arch dam, the structure was assumed to be made up of arch and cantilever elements. The procedure used in the formation of these elements was essentially the same as that adopted for the method of trial loads (7). The arches and cantilevers were assumed to be fixed where they contact the foundation rock. Inertia and flexibility properties of an arch dam have also been determined by the finite element method (8).

As is usually done in the solution of complex structural-dynamic problems, the total mass of the structure was divided into a system of lumped masses. These were concentrated at the points of intersection of the centerlines of the two structural elements, except at the crest where the lumped masses were applied at the top-center of each cantilever. Also assumed to be concentrated at each mass point was the virtual water mass which oscillates with each of the lumped concrete masses. The distribution of the virtual water mass with depth was computed by Westergaard's method (9). The inclusion of the virtual water mass in the solution of the seismic loading problem for arch dams takes into account the transient reservoir pressures on the upstream face of the structure. Other methods for computing these pressures are discussed in Reference 6. Chapter 6.

To determine the flexibility of an arch dam, structural continuity was established in the radial and tangential directions at each mass point by equating, respectively, the arch and cantilever unit-load deflections for these two directions. The deflection relations included bending and rib-shortening deformations for the arches and bending and shear deformations for the cantilevers. The relations did not include deformations caused either by rotations of the two structural elements or by foundation movements. These two deformations are usually accounted for in a complete stress analysis of an arch dam. To simplify electronic computation of the inertia and flexibility properties of the dam the equations defining these properties were expressed in matrix form.

The flexibility of an arch dam depends in part on the modulus of elasticity (E-value) for the mass concrete in the dam. For a dynamic analysis it was decided that E-values based on dynamic measurements, in situ, would be preferable to E-values determined from static tests on concrete specimens. Accordingly, data on dynamic E-values were obtained from geophysical measurements of longitudinal wave speeds through the mass concrete in two arch dams. The results of these tests and the corresponding E-values from static tests are: Monticello Dam concrete, E (dynamic) = 5.1×10^6 psi and E (static) = 4.8×10^6 psi (from laboratory tests on 10-inch-diameter, 2-year old specimens); Morrow Point Dam concrete, E (dynamic) = 4.7×10^6 psi and E (static) = 4.7×10^6 psi (from laboratory tests on 10-inch-diameter cores drilled from the dam). For the computation of E (dynamic) from the measured wave speeds, Poisson's ratio and the unit weight of mass concrete were taken as equal to 0.20 and 150 lb per ft^3, respectively.

The mass and flexibility matrixes were used in the solution of the natural frequencies and mode shapes. Since the problem for evaluating these two quantities is an eigenvalue problem, they were computed directly on an electronic computer using a standard program.

In an attempt to check the method for determining natural frequencies and mode shapes of an arch dam, comparisons were made between measured and computed data. The measured data were obtained in 1965 during the forced vibration tests on Monticello Dam, a 304-foot high arch structure located near Sacramento, California (10). The computed data used for the comparison were obtained from two dynamic-response analyses of this dam, one for the water surface 23 feet below the crest (the location of the water surface during the tests) and the other for no reservoir water (11). The experimental and computed natural frequencies for Modes 1 through 5, respectively, are:

1. Experimental: 3.12, 3.55, 4.63, 6.00, and 7.60 Hz

2. Computed, reservoir water 23 feet below crest: 2.75, 2.88, 4.09, 5.11, 6.28 Hz

3. Computed, no reservoir water: 3.86, 3.89, 5.55, 6.54, and 8.20 Hz

Comparisons of experimental and computed mode shapes for the crest and three cantilevers for Mode 1 are given in Figure 1.

When investigating an arch dam for earthquake loadings, the response of the structure for several design earthquakes is often desired. So that this can be done efficiently, stresses were obtained at each mass point for a 1-ft per sec^2 acceleration applied at each of these points. (The total seismic stresses were based on accelerations for directions parallel and normal to the tangent to the dam axis at the crown.) To compute these stresses, inertia forces for the unit accelerations were found for each mass point using mode-shape and mass-distribution data. Since inertia forces may be treated as static forces, modal stresses at the mass points were determined by the "Arch Dam Stress Analysis System" (ADSAS), which was developed by the Bureau of Reclamation for making static-load stress analyses of arch dams by means of electronic computers.

Having modal stresses for a unit acceleration, modal stresses for any time-dependent earthquake accelerations may be obtained by the application of the Duhamel integral. For the present solution, values of the integral were computed for each 0.01 second of the acceleration trace. To obtain the modal stresses for any mass point for any time of the acceleration trace the value of the integral for that time was multiplied by the unit acceleration modal stress computed for the point. The corresponding seismic stress values were obtained by adding the modal stresses for earthquake accelerations acting in the two directions mentioned above. For the purpose of the analysis, cantilever stresses (vertical) and arch stresses (horizontal) were evaluated.

To obtain the combined stresses the static-load stresses determined by ADSAS were superimposed on the seismic stresses. Only the maximum stress values and the times when they occur were listed.

To compute seismic stresses for an arch dam, data on structural damping are required. This property, which is not constant for all modes, must be obtained experimentally. Modal damping values for an arch dam were determined for small displacements from the frequency-response data measured during the Monticello Dam forced vibration tests. These values range from 2.1 percent critical for the fourth mode to 2.7 percent critical for the first mode. Whether structural damping changes for large displacements, has not yet been determined. Okamoto reports in Reference 12 that damping equal to 4 percent critical was found for the first mode from data recorded on Tonoyama Dam, a thin arch structure, during an earthquake. The damping value presently used by the Bureau of Reclamation for the design of arch dams is 3 percent critical (all modes).

CONCLUSIONS

1 The method of analysis outlined here is satisfactory for determining seismic stresses for arch dams. Seismic stresses computed by the method, however, are only meaningful for the time of application of the design earthquake during which the deformations of the dam for dynamic and static loadings are elastic.

2. Comparisons between computed and experimental natural frequencies and mode shapes show that the method gives satisfactory values for these quantities.

3. Comparisons of moduli of elasticity values based on in situ longitudinal wave speed measurements in the mass concrete of two dams and on static tests on laboratory specimens of the same concrete indicate that the static and dynamic moduli of elasticity for mass concrete are approximately the same.

4. A reasonable value of structural damping for arch dams is 3 percent critical.

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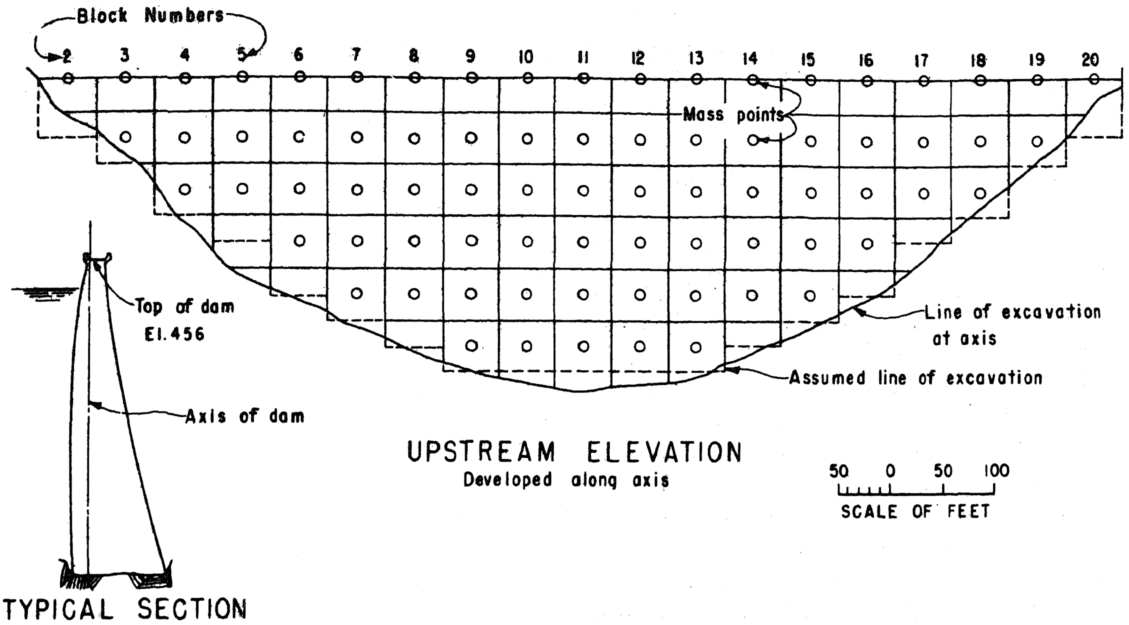
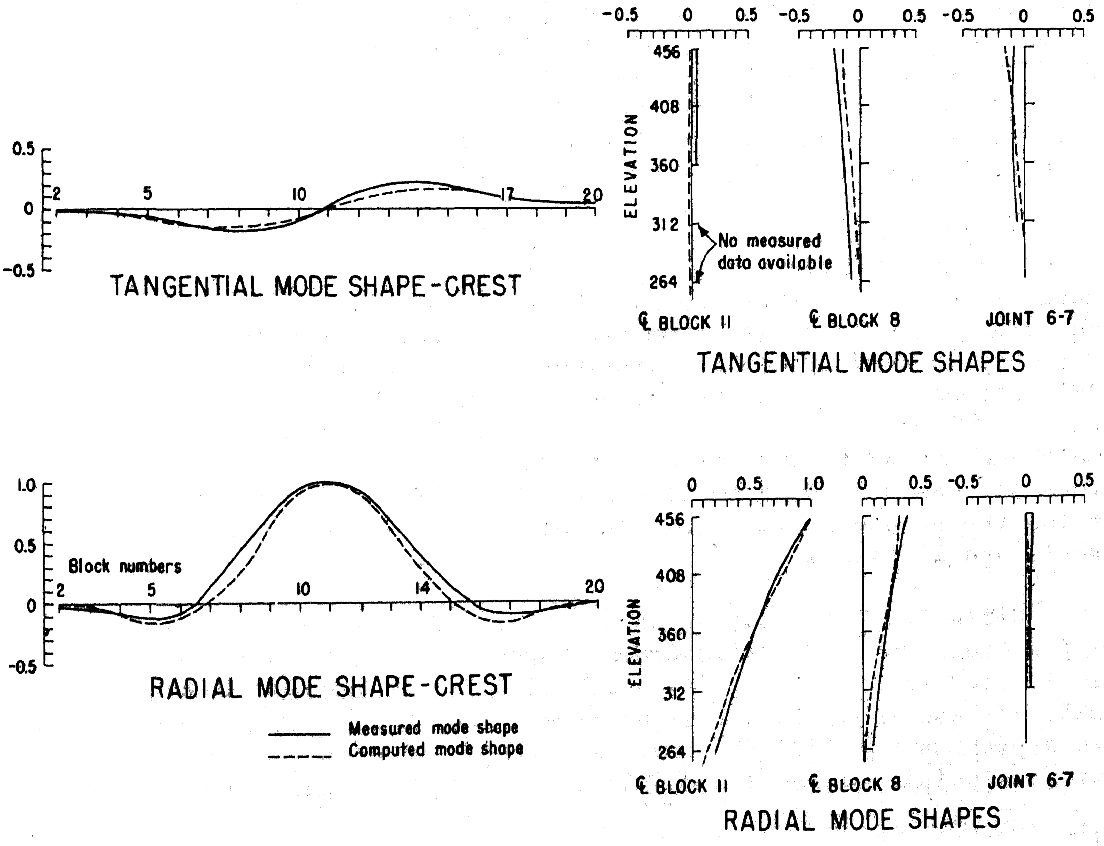

UPSTREAM ELEVATION
Developed along axis

TYPICAL SECTION

ELEVATION AND SECTION OF MONTICELLO DAM


TANGENTIAL MODE SHAPE-CREST

TANGENTIAL MODE SHAPES

RADIAL MODE SHAPE-CREST

RADIAL MODE SHAPES

FIG. 1 COMPARISON OF MEASURED AND COMPUTED MODE SHAPES
MONTICELLO DAM - FIRST MODE