Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VII)

12-4-16

THE SEISMIC REINFORCEMENT OF GIBRALTAR ARCH DAM

Noel C. WONG[1], John A. BISCHOFF[1], and J. Frank CALLANAN[1]

[1] Woodward-Clyde Consultants, Oakland, California, U.S.A.

SUMMARY

Gibraltar Dam is a 67 year-old concrete arch dam on the Santa Ynez River in Santa Barbara, California, U.S.A. The owner has been required to strengthen the dam for protection against seismic hazard. Based on detailed design studies, the addition of a roller compacted concrete buttress downstream of the dam was selected as the dam strengthening scheme. This paper summarizes the design rationale, and the analysis carried out to verify the design of this unique dam strengthening project.

INTRODUCTION

Gibraltar Dam is a constant radius concrete arch dam located on the Santa Ynez River in Santa Barbara County, about 14 km north of the City of Santa Barbara (City), California, U.S.A. (Photo 1). It was constructed in 1920 to provide storage for the City's municipal water supply. The dam has a maximum height of 59.3 m and a crest length of about 183 m (Fig. 1). The thickness of

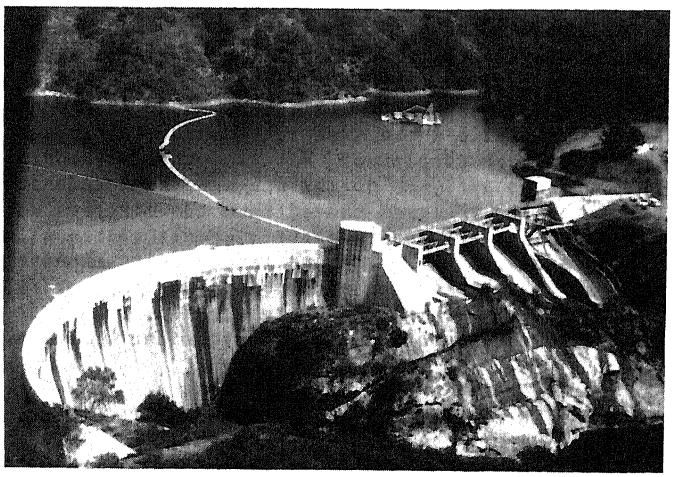


Photo 1 Gibraltar Dam, Santa Barbara, California, U.S.A.

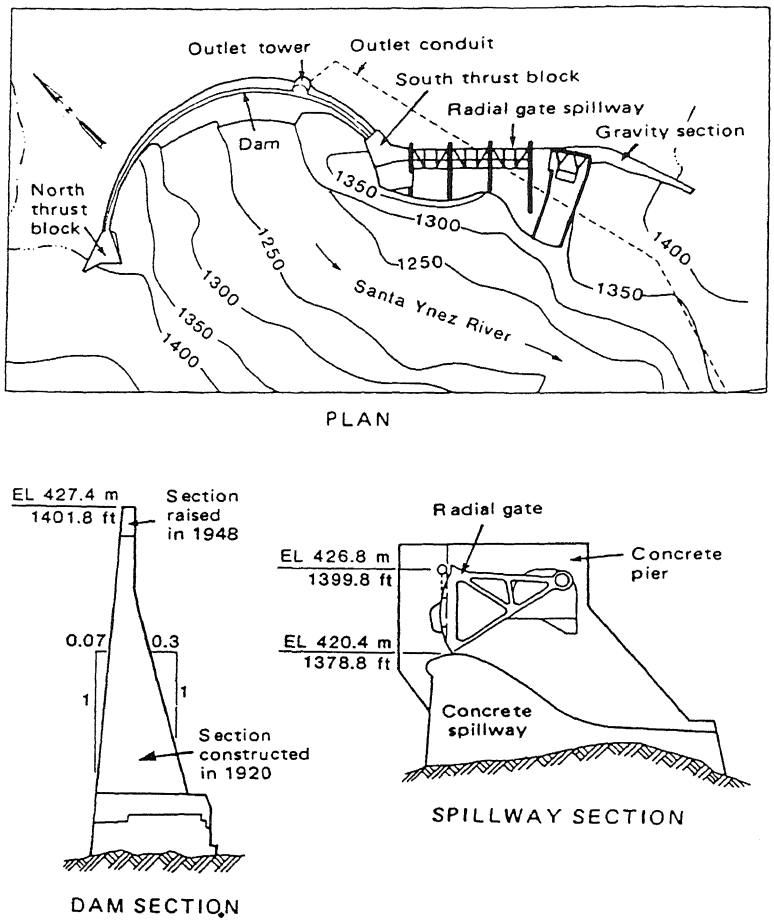


Fig. 1 Plan and Sections of Existing Dam

the dam varies from 2.1 m at the crest to about 20 m at the base. In 1979, the California Division of Safety of Dams (DSOD) directed the City to re-evaluate the stability of the dam for the extreme loading conditions of the Probable Maximum Flood (PMF) and the Maximum Credible Earthquake (MCE). As part of the stability evaluation, extensive field exploration, laboratory testing, and stability investigations were completed. Detailed three-dimensional finite element method (FEM) stress analyses of the dam and the foundation were carried out. The results of the FEM analyses showed that the stresses which would develop in the dam under the MCE loadings are higher than the allowable tensile strength of concrete, and as such the dam no longer meets the present seismic safety standard of dam design. Consequently, in order to avoid a potential mandatory reduction of storage owing to safety considerations, it was agreed by the City and DSOD that the City would strengthen the dam by December 1989.

EVALUATION OF ALTERNATIVE STRENGTHENING SCHEMES

Three alternative remedial schemes for strengthening the existing dam to withstand loadings corresponding to the MCE were identified (Ref. 1). The three alternatives included: (1) the addition of a roller compacted concrete (RCC)

buttress on the downstream face of the dam; (2) the addition of a reinforced rockfill embankment on the downstream face of the dam; and (3) the addition of a steel fiber reinforced shotcrete "blanket" on the upstream and downstream faces near the top of the dam (Fig. 2). The strengthening options were evaluated in terms of the overall effectiveness of each concept, the geometric constraints of the downstream terrain, the impact of potential overtopping flood flows, the effect of construction on the operation of the reservoir, the availability and quality of construction materials, the time and cost of construction, and the potential environmental impacts.

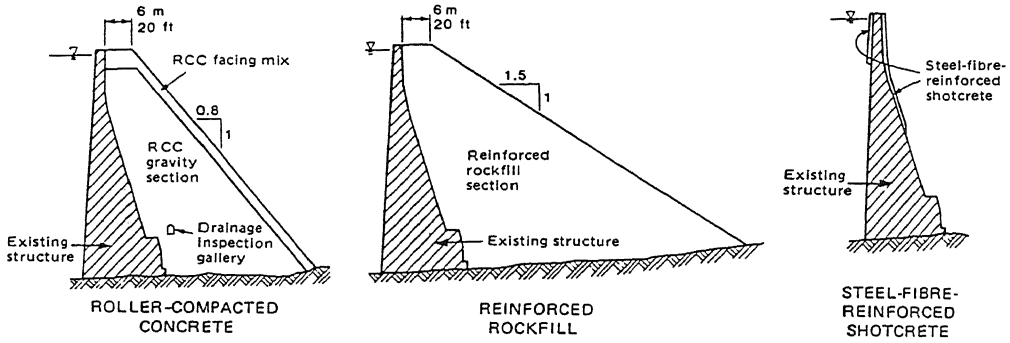


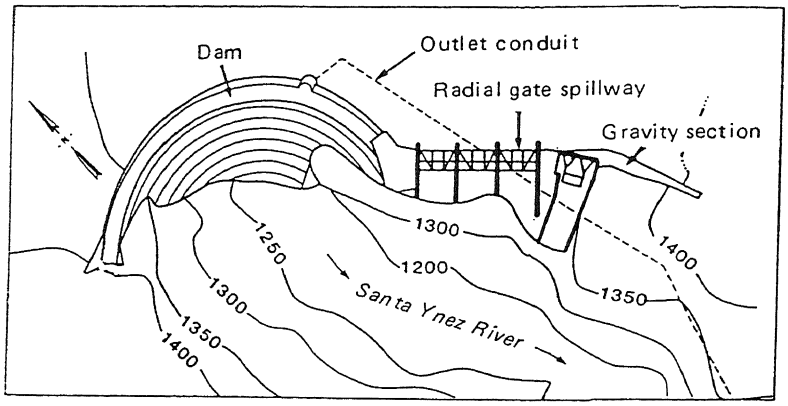
Fig. 2 Alternative Strengthening Measures

Of the three options, the use of RCC was considered to be the best approach based on the above described considerations. In essence, the proposed modification converts the existing arch dam into a curved gravity dam (Fig. 3). The modified structure would be stiffer and more massive than the existing dam, and the resulting dynamic response would be less, with the stresses induced in the dam under earthquake loadings being reduced. Because of its strength, RCC could be placed at a steeper angle, and the required volume of material would be less than conventional earth and rockfill embankments. The proposed strengthening project is considered to be unique from two points of view: (1) the seismic strengthening of concrete arch dams, and (2) the application of RCC construction. In order to provide the necessary design information, a comprehensive laboratory testing program on the evaluation of construction materials and RCC mix design was carried out (Ref. 2). For further evaluation of constructability and RCC testing, a field study involving the construction of s full-scale RCC test section was carried out (Ref. 3). Detailed three-dimensional FEM analyses were also carried out to verify the proposed dam strengthening design.

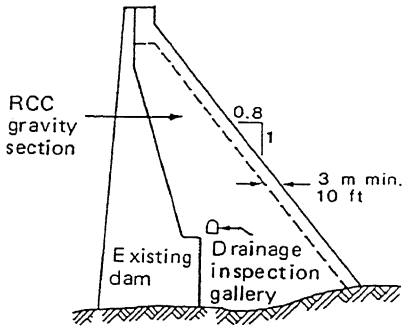
ANALYSES OF STRENGTHENED DAM

The three-dimensional FEM stress analyses of the strengthened Gibraltar Dam were carried out to verify that the modifications would be sufficient to ensure that the dam would perform safely under critical static and dynamic loadings. The analyses were used to determine the potential deformations and stress distributions in the strengthened dam under static PMF loadings, and the design MCE loadings.

Method of Analysis The stress analyses were carried out using the computer program EASE2. EASE2 is a "SAP IV" type general structural analysis program for the static and dynamic linear elastic finite element analyses of structural systems (Ref. 4). Two types of elements were used to model the structure:



PLAN



DAM SECTION

Fig. 3 Plan and Section of Strengthened Dam

solid elements and membrane elements. Solid elements are eight-node or six-node elements. Each node has 3 translational degrees of freedom. An integration order of 2 was specified for right prism solid elements, and an integration order of 3 was specified for skewed solid elements and wedge elements. Membrane elements are four- or three-node, and are treated as 2-dimensional plane elements which resist in-plane distortion only.

Finite Element Model The 3-dimensional finite element model of the strengthened dam and its foundation was developed based on the geometry of the existing arch dam and thrust blocks, and the proposed RCC buttress configuration. Brick elements were used for modeling the main body of the dam, and wedge elements were used to model some of the contact locations of the dam with the foundation rock. Membrane elements with minimal thickness were added to the upstream and downstream (interface) surfaces of the existing dam and downstream surface of the RCC section. The membrane elements were defined using the same nodes as the solid elements. The use of membrane elements facilitates the calculation of stresses in convenient arch and cantilever directions. The dam foundation has been included in the FEM model because portions of the foundation bedrock have relatively low moduli. The foundation has been modeled with solid elements as a massive unit extending below the dam, and upstream and downstream in a radial direction. A section of the spillway was included in the foundation model so boundary restraint conditions applied to the foundation at this location would not influence the behavior of the south (left) abutment

thrust block. Pinned supports (no translation) were applied at the nodes along the sides and base of the foundation.

Static Stress Analyses The static stress analyses of the strengthened dam were performed considering several combinations of internal and external loadings to the 3-D FEM model. Internal loadings consisted of the dead weight of the dam and uplift pressures acting at the base of the dam. External loadings consisted of hydrostatic pressure corresponding to reservoir, tailwater and silt fluid pressures. The maximum deformation of the crest of the dam in the downstream direction under the PMF loading is about 4 mm. The maximum compression and tension stresses developed on the upstream face of the dam are 0.7 and 0.3 MN/m^2, and 1.1 and 0.1 MN/m^2 on the downstream face, all of which are well within the strengths of concrete and RCC.

Dynamic Stress Analyses The dynamic analyses consisted of frequency calculation and time history response analysis. The frequency analysis required calculation of the periods of the various modes of vibration of the structure. The response history analysis required the dynamic time-history analysis of the dam using ground motions corresponding to the extreme seismic loadings.

The hydrodynamic effects of the reservoir and fluid silt were approximated using the Generalized Westergaard's "added mass" approach (Ref. 5). The normal maximum reservoir condition was considered and the added masses were calculated by applying the Generalized Westergaard formula to the contributory area of each node on the upstream face of the dam and abutments. The associated volume of water was then converted to an equivalent added lump mass attached to the node, acting normal to the upstream face of the dam.

The frequency analysis is basically a computation of the eigenvalue of the system. Program EASE2 was used to calculate the natural frequencies of vibration, vibration mode shapes and mass modal participation factors by solving the generalized eigenvalue problem using the subspace interaction technique. The number of eigenvalues to be calculated depends on the number of modes to be included in the time-history analysis, and consideration of the first 5 to 10 modes is sufficient for the analysis of a gravity dam. In the analysis of the strengthened Gibraltar Dam, the first 8 modes were used. The calculated frequencies of the first 3 modes of the strengthened dam are 5.55, 7.12 and 8.96 Hz. The mode shape plots of the first two modes of the strengthened dam are shown in Fig. 4.

The time history analysis of Gibraltar Dam was performed using the mode superposition method. The maximum dynamic tensile cantilever and arch stresses

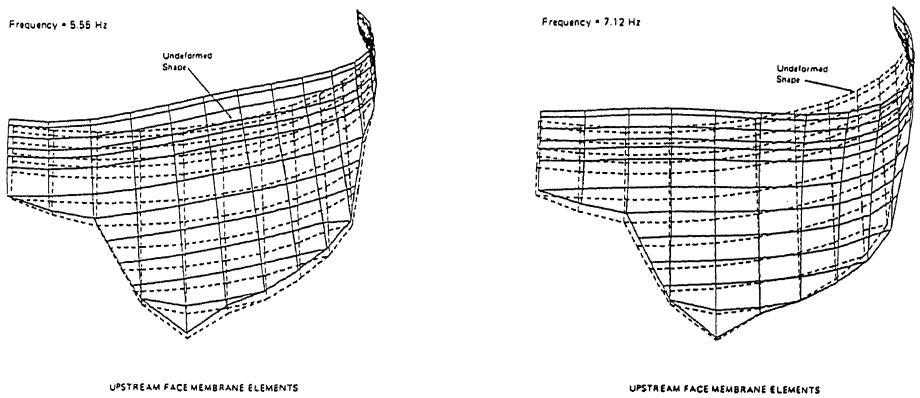


Fig. 4 Vibration Modes Shapes

developed on the upstream face of the dam are 4.8 and 4.3 MN/m^2, and 3.4 and 4.8 MN/m^2 on the downstream face. In order to evaluate the overall performance of the strengthened Gibraltar Dam, both the overall stress distribution in the structure during peak stress response and the resulting total stress when combined with the static stress components were examined.

Certain areas in the upstream and downstream faces of the dam experience stress levels higher than the assumed dynamic tensile strengths. The maximum combined (static and dynamic) tensile cantilever and arch stresses in the dam corresponding to the peak responses are 4.4 and 3.7 MN/m^2 on the upstream face, and 2.2 and 4.5 MN/m^2 on the downstream face. The analyses show that the exceedances occur two or three times for short durations (less than 0.04 seconds) during the first 10 seconds of high level ground shaking. It is also noted that the stresses at the center of the solid elements immediately adjacent to the membrane elements on the upstream and downstream faces are less than the stresses for the membrane elements, and are within the strengths of concrete and RCC.

CONCLUSIONS

The results of the FEM stress analyses show that the stress distributions for the strengthened Gibraltar Dam are reasonable, and their magnitudes are expected to stay within the established RCC and concrete strength criteria. Although some minor surface cracking may occur, the existing dam strengthened by the addition of a RCC buttress will be able to withstand the MCE loading with no catastrophic failure characterized by a sudden dam collapse and release of reservoir water. The construction of the RCC buttress has in this case promised to be a very efficient method of strengthening an existing arch dam.

ACKNOWLEDGMENT

The preparation of this paper is sponsored by the Professional Development Program of Woodward-Clyde Consultants. The support provided by the Sponsoring Principals is greatly appreciated. The authors also express their sincere thanks and appreciation to the City of Santa Barbara for permitting the authors to present the materials contained in this paper.

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