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A REVIEW AND ANALYSIS OF AAR-EFFECTS IN ARCH DAMS

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ABSTRACT

A review of the effects of alkali-aggregate reaction (AAR) in arch dams is presented. Numerous arch dams in the United States, Africa, Portugal and Spain have AAR and this paper presents a summary of observed/measured behavior of the dams.

From the review, it is shown that arch dams can experience relatively large deformations and the displacement pattern is quite unique. A detailed finite element analysis of a typical arch dam is undertaken to demonstrate the mechanisms of behavior. From the analysis, it is shown that the stress-dependent behavior of AAR concrete expansion is a very important consideration for the proper analysis of arch dams. For example, an analysis which neglects the stress-dependent nature of concrete growth will significantly over-estimate the amount of tension in the dam. In addition, the unique displacement pattern of an arch dam with AAR is well matched by a finite element analysis which includes the stress dependent concrete growth behavior.

Keywords: AAR, alkali-aggregate reaction, arch dam, finite element analysis, stress-dependent.

INTRODUCTION

A number of case histories which discuss observations of AAR in arch dams are available in the literature. However, very little information is given on analysis of the effects of AAR in these dams. The case histories have shown that most of the AAR-affected arch dams are behaving in a similar manner and the results of finite element analysis of these structures are not correlating well to field measurements.

The objective of this paper is to present an illustrative analysis of an arch dam subjected to AAR-induced expansion. In addition, a brief review of the some case histories is presented.

REVIEW OF CASE HISTORIES

The following case histories of AAR-affected arch dams are briefly described:

- Kouga Dam in South Africa
- Gene Wash Dan in California, USA
- Copper Basin Dam in California, USA
- Cahora-Bassa Dam in Mozambique
- Santa Luzia Dam in Portugal
- Alto-Ceira Dam in Portugal
- Fontana Emergency Spillway in North Carolina, USA

A brief summary of significant features and response of each of the above dams is given in the following subsections.

Kouga Arch Dam

A recent paper (Elges et al. 1995) provided the following information. Kouga arch dam is located near Port Elizabeth in South Africa. The dam is 78 m high with a crest length of 317 m. The construction of the dam was completed in 1969.

Geodetic measurements are used to monitor the deformation response of the dam. Both vertical and horizontal displacements are measured. The measurements indicate that concrete expansion became detectable by 1976 and the rate of expansion appears to be slowing since about 1984. A comparison of horizontal deformation measurements at the upper gallery in 1984 and 1994 (at the same time of year and at approximately the same reservoir water level) indicates the largest change in displacement occurs near the quarter points and relatively small displacement change occurs at the centerline of the dam. The profile of horizontal displacements is shaped somewhat like an 'M' with the largest displacements occurring near the quarter points. It is interesting to note that other papers (Ramos et al. 1995) make reference to an 'M' profile of vertical displacements in arch dams subjected to swelling processes.

At Kouga Dam, there is considerable variation in temperature and reservoir water level. It is considered very important to include these effects in a detailed analysis of the structure.

Finite element modeling of the dam used an equivalent temperature load to simulate concrete expansion. A linear elastic analysis of the dam was able to provide a reasonable match to displacement measurements but concrete stresses up to 5 MPa tension were computed. A nonlinear no-tension model was unable to match the observed displacements.

Gene Wash and Copper Basin Dams

A recent paper (Hill 1995) presented a summary of the response of Gene Wash and Copper Basin arch dams to AAR-effects. These dams are located in San Bernardino County, California and they were constructed in the late 1930's.

Gene Wash dam is 40 m high (131 ft) with a crest length of 131 m (430 ft), including the gravity thrust block. From 1942 to 1965, the dam height near the centerline increased by about 90 mm (0.3 ft). However, from 1965 to 1995, the height of the dam has increased only by 8 mm. Similarly, the horizontal upstream movement of the crest near the centerline of the dam changed by 110 mm from 1942 to 1965, but after 1965 the monotonic component of the movement has ceased. The change in height of 90 mm from 1942 to 1965 represents a concrete growth rate of about 100 $\mu\epsilon$/year.

Copper Basin dam is 57 m high (187 ft) with a crest length of 77 m. Copper Basin has experienced deformations similar to those measured at Gene Wash. From 1942 to 1955, the height of the dam near its centerline has increased by about 90 mm (representing a concrete growth rate of about 120 $\mu\epsilon$/year). After 1955, the concrete growth rate has decreased and from 1955 to 1995 the height has changed by 21 mm (or an average of about 10 $\mu\epsilon$/year). The upstream movement from 1942 to 1955 was 110 mm (0.36 ft) and 11 mm (0.036 ft) from 1955 to 1975. After 1975, the concrete growth induced movements appear to have ceased.

An interesting feature in both dams is a series of inclined cracks adjacent to the abutments in the upper portion of the dam. The cracks are oriented at approximately the same angle as the abutment profile adjacent to the crack. The cracks are believed to be caused by the greater upward deformation in the central portion at the dam relative to the abutments due to a greater height of concrete.

Cahora-Bassa Dam

A report on Cahora-Bassa arch dam was presented in a recent paper (Ramos et al. 1995). Cahora-Bassa Dam is a 170 m high arch dam with a crest length of 300 m. The dam is located in Mozambique and it was constructed between 1971 and 1974.

Measurements from no-stress strain meters are available from 1975 and precise leveling data is available from 1977. The no-stress strain meter data indicate the effects of concrete swelling became measurable in 1979. The measured expansions correspond to rates of expansion of about 13 to 26 $\mu\epsilon$/year. The precise leveling measurements indicate a height increase of 11 mm from 1977 to 1994 over a concrete height of about 125 m. This height change represents a concrete growth rate of about 6 $\mu\epsilon$/year. The profile of measured vertical displacement changes from the precise leveling is symmetric about the centerline of the dam. The results from the no-stress strain meters were used to establish zones of swelling strain and evolution of swelling in the dam. It is interesting to note that the zones were such that more concrete expansion was measured at the quarter points along the arches rather than at the center of the dam.

Santa Luzia Dam

Santa Luzia dam in Portugal is a cylindrical arch dam with a maximum height of 76 m and crest length of 115 m (Ramos et al. 1995). The dam was completed in 1943.

The maximum vertical displacement change over 40 years is about 50 mm (corresponding to a expansion strain of about 16 $\mu\epsilon$/year). Over the same period the crest of the dam has translated horizontally about 30 mm upstream. The profile of vertical displacements is in the form of an 'M' shape, i.e., the maximum vertical displacement occurs near the quarter points along the crest.

Alto-Ceira Dam

The response of this dam to AAR effects is also given by Ramos et al. (1995). The Alto-Ceira dam is also located in Portugal and it was constructed in 1949. The maximum height of the dam is 37 m and it has a crest length of 120 m.

From vertical displacement changes, an expansion of 1600 $\mu\epsilon$ was computed. An accumulation of 1600$\mu\epsilon$ expansion corresponds to an expansion rate of 40 $\mu\epsilon$/year assuming that the accumulated strain developed over 40 years. The analysis of the dam used measured displacements to estimate input expansion strains. The dam was subdivided into six zones and different expansion initial strains were applied to each zone.

As a result of reliability concerns, the possible need to abandon the dam and to build a new dam downstream of the existing dam was reported to be under consideration. The old dam (Alto-Ceira) would serve as a cofferdam for the new dam.

Fontana Emergency Spillway

A case history study of the Fontana Emergency Spillway is given in a recent paper (Yeh et al. 1993). The Emergency Spillway is a 16.8 m high single curvature arch structure located in North Carolina, USA.

Measurements of upstream movement indicate the crest has translated over 400 mm upstream as of 1991. The rate of upstream movement developed gradually and from the late-seventies until now the rate of upstream movement is about 19 mm/year. A total vertical expansion of 63 mm was reported. The vertical deformation seems inconsistent with the large horizontal displacement. Such a difference between horizontal and vertical movements implies a large variation in concrete growth through the thickness of the arches causing bowing. There are also reports of some diagonal cracking in the dam.

The analysis of the dam was undertaken using a linear finite element model and the concrete growth was simulated with an equivalent temperature load. The input equivalent temperatures were determined from a back-analysis of field measurements. The results of the analysis provided a reasonable match to horizontal deformations but computed stresses and thermal movements exceeded measured values by a factor of 3 to 4.

Discussion of Analysis of AAR-Affected Arch Dams

The case histories presented in the preceding subsection have demonstrated some key issues as follows

- back-analysis of AAR-affected arch dams using linear FEA methods with equivalent thermal loads has been unsuccessful;

- FEA has not provided an understanding of the behavior of AAR-affected arch dams, therefore although the effects of AAR may be moderate, the owner of the dam is uncertain of its actual condition;

- previous analyses could not estimate the stress-state in an AAR-affected arch dam, therefore the need and type of remedial measures could not be identified. For the same reason the safety levels in the dam could not be quantified.

It is important to note that the stress-dependent nature of concrete growth will be very significant in arch dams. In an arch dam under normal loading conditions, there is considerable variation in stress through the thickness of the dam, i.e., bending causes stress variation through the thickness as a result of arch and cantilever action. The stress variations through the thickness of the dam leads to significant variations in concrete growth rates. In additions, the variations in stress and directions of gradients vary depending on location in the dam and reservoir water level. These variations in stress and concrete growth rates will have a very significant effect on the response of the dam to AAR loads. Therefore, a stress-dependent concrete growth model such as GROW3D would provide a better match to deformations and meaningful stresses would be computed. The GROW3D finite element program was developed to analyze AAR-affected mass concrete structures such as dams, powerhouses and locks. The time dependent analysis results are used to assess the present and future stress condition of the structures and to estimate levels of safety.

An illustrative analysis of an arch dam using the GROW3D finite element program is presented in the next section. A hypothetical dam shape is selected for illustration purposes.

ILLUSTRATIVE ARCH DAM ANALYSIS USING GROW3D

It is interesting to note that the GROW3D finite element program was originally developed using an existing arch dam analysis finite element program as the solver. Initially, the program EADAP was modified to include higher order elements, nonlinear no-tension analysis capabilities, and improved stress recovery methods. Subsequently, the program was modified to include stress-dependant concrete growth behavior and a more efficient equation solver. The new program GROW3D has been used to analyze numerous AAR-affected structures including gravity dams, spillways and powerhouses (Curtis 1995).

The hypothetical dam has a height of 80 m and a total crest length of 300 m. The foundation rock is assumed to be relatively stiff with a uniform elastic modulus of 30 GPa. The dam concrete has a instantaneous elastic modulus of 28 GPa and creep effects are addressed using an effective modulus approach. The dam and foundation are modeled with 20-noded solid elements and 15-noded wedge elements at the dam/foundation interface. The concrete growth strains are computed at the integration points in each element using the principal stresses at each integration point. This approach leads to a substantial variation in applied initial strain load within each element because of the variation in stress through the thickness of the element. It is noted that such a variations in initial strain through the thickness of an element can cause relatively large deformations without large increases in stress depending on boundary conditions and the geometric configuration of the dam.

The initial step in the analysis is to estimate the initial stress state in the dam. For this illustrative analysis both dead load and hydrostatic loads are applied to the dam. The hydrostatic load was applied over a height of 70 m. In this case the effect of temperature changes have not been included, however this could be included in a detailed analysis of an existing dam.

A modest amount of concrete growth has been assumed in this example. A stress-dependent concrete growth function was used in the analysis (described further in Charlwood et al. 1992 and Thompson et al. 1994) The concrete growth strain varies with the logarithm of concrete principal stresses. The relationship between concrete growth rate $\epsilon_{gi}(t)$ and principal stress is given in Equation 1 below.

[1]
$$\varepsilon_{gi}(t) = \varepsilon_{go}(t) - K\left[\log\left(\frac{\sigma_i}{\sigma_o}\right)\right]$$

where

$\epsilon_{gi}(t)$ = the unrestrained concrete growth rate at low stress at time (t)
K = the slope of the line defining the concrete growth rate versus the log of stress
σ_i = the three principal stresses (i = 1 to 3)
σ_o = a low compressive stress cut-off whereby at lower compressive stresses or any tensile stress, the concrete growth rate is set at the unrestrained rate and, at larger compressive stresses, the concrete growth strain rate is reduced according to the above logarithmic function.

The concrete growth strain rates, $\epsilon_{gi}(t)$, at each time interval are resolved to the direction of the principal stresses. These strain rates are the initial strain loads (internal loads) used in the finite element analysis of a given time step. The following constants define the concrete growth law:
ϵ_{go} = 33 $\mu\epsilon$/yr
σ_o = 0.3 MPa

The stress which completely suppresses concrete growth expansion is assumed to be 5 MPa and this is used to determine the slope K in Equation 1. The stress required to suppress concrete expansion was estimated from experience obtained from analysis of other AAR-affected structures (Curtis 1995).

The concrete growth is stepped through time using one year time increments. The results of the analysis are presented on sections through the upper arches forming the top surface of each solid element. This presentation approach provides an illustration of results through the thickness of the dam and also over the height of the dam. The approach is well suited to the presentation of arch dam analysis results because of the relatively small thickness of the elements. The results of the GROW3D analysis were output at time step 14 and time step 25.

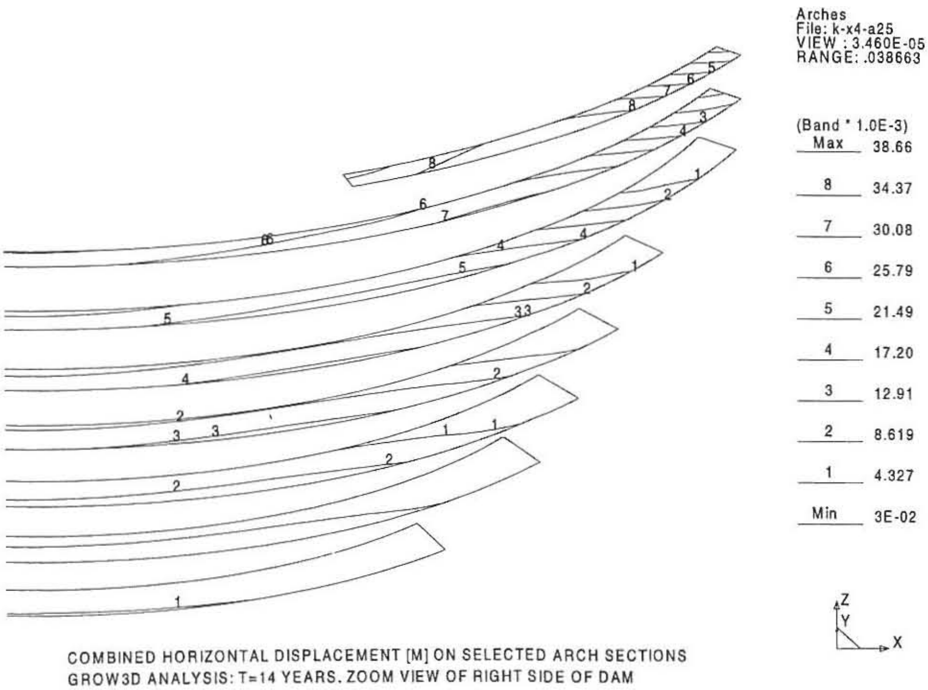

Fig. 1: Contours of combined horizontal displacement (T = 14 years)

Contours of combined horizontal displacement due to concrete growth are presented in Fig. 1. From Fig. 1, the maximum displacements occur at the quarter points in the upper portion of the dam. The model is capturing the 'M' pattern of horizontal displacements which is observed at other arch dams. It is noted that a detailed analysis of an AAR-affected arch dam should include more elements through the thickness of the dam and this would probably amplify the computed displacements at the quarter points slightly. The maximum computed displacement is about 20 mm.

The computed global stresses are resolved into arch and cantilever directions and principal stresses are computed at the face of the dam. The arch stresses are presented in Fig. 2. It is noted that compression is negative. From Fig. 2, the maximum compressive arch stress is -4.6 MPa. A comparison to the initial stress condition at time step 0 shows that the stresses in the lower portion of the dam increased by up to about 1.0 MPa compression and the only small stress changes occurred in the upper portion of the dam.

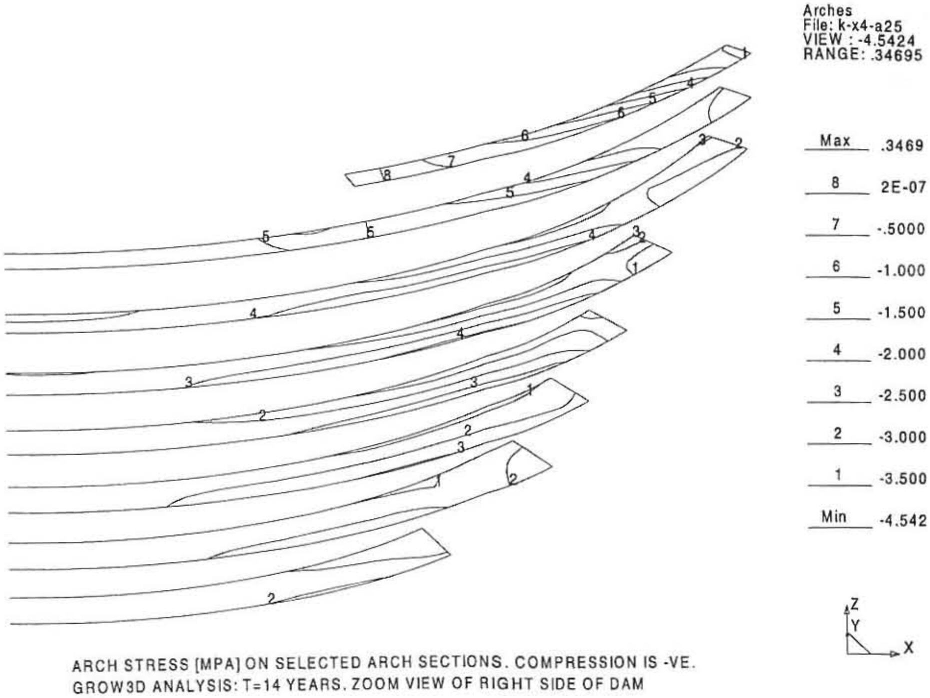

Fig. 2: Contours of arch stresses (T = 14 years)

The cantilever stresses are presented in Fig. 3. From Fig. 3, the cantilever stresses vary from 0.7 MPa tension to -3.7 MPa compression. It is interesting to note that initial stress condition without AAR loads showed some tension at the base of the dam at the upstream face and AAR expansion has eliminated this tension. The AAR loading has caused the dam to move upstream and this increases the compression on the upstream face and reduces the compression on the downstream face. It is important to note that as the compression on the downstream face is reduced, the rate of concrete growth increases thus large tensile stresses do not develop in this case, i.e., the rate of concrete growth increases with lower compressive stresses due to stress-dependent growth. From Fig. 3, some tensile stresses appear on the downstream face in the upper portion of the dam. Some tension is expected at these locations as the central portion of the dam expands over a greater height than the sections of the dam near the abutments.

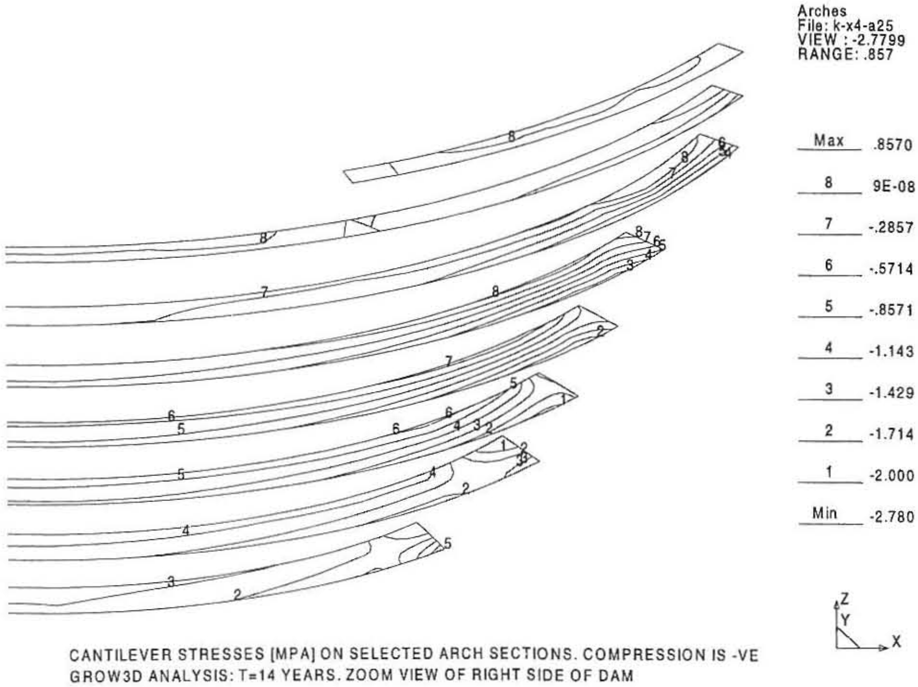

Fig. 3: Contours of cantilever stresses (T = 14 years)

A review of the stress results at time step 25 showed an increase in stresses particularly at the lower portion of the dam. The maximum increase in stresses in the arch direction is about 1.5 MPa compression. The maximum tensile stress in the cantilever direction increased to about 1 MPa.

CONCLUSIONS

The results of the illustrative analysis of a hypothetical arch dam indicate that moderate amounts of concrete expansion can cause displacements of significant magnitude without causing large increases in concrete stresses. The stress condition can be improved by the development of compressive stress in the areas where tension could occur otherwise. For example, at the upstream base of the crown cantilever a condition of low tensile stress can be improved to a compressive stress state due to the upstream deformation caused by AAR. However, tensile stresses can increase near the abutments due to the rise of the central portion of the dam. In addition, the modeling of stress-dependant concrete growth allows the concrete expansion to vary significantly through the thickness of the dam and this type of initial strain loading can cause relatively large deformations without creating large stresses.

The demonstration analysis presented herein indicates that a stress-dependent concrete growth model program may be used to understand the structural response of arch dams subjected to AAR. The modeling of stress-dependent concrete expansion and enhanced creep behavior are important. In addition, the model may be used to estimate the stress state in the dam and thus the safety of the dam can be assessed.

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