Numerical Simulation for the Mechanical Behaviors of a Concrete Dam with Consideration of Alkali-Aggregate Reaction

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***Abstract*—Alkali-Aggregate Reaction (AAR) is one of the phenomena that during the life time of concrete, endangers it, and is one of the factors that cause serious damages to wet concrete structures, such as concrete dams. The most important structural effect of this reaction is the creation of strain in concrete due to expansion of concrete. In this paper, in order to evaluate the effect of AAR, one of the gravity dams at Beauharnois power plant, which showed signs of this reaction, was studied, and a software program based on finite element was used. In this paper, the dam is analyzed assuming that AAR does not occur. Then the dam with the case that is analyzed considering this reaction, the results were evaluated and compared. This comparison shows a big difference between the results of the two conditions, and that expresses the substantial effect of AAR on the dam. Displacements are some of these effects.**

***Index Terms*—alkali-aggregate reaction, concrete dam, numerical analysis, displacement, result comparison**

I. Introduction

Nowadays, discussion and analysis about Alkali-Aggregate Reaction (AAR) in concrete structures with regards to dam safety and the substantial amount of repair expenses, are highly regarded [1]. AAR problems have been reported all over the world, and no country seems to be immune from this disease (though structures in relatively colder climates have been slower to develop this reaction). [2]

The phenomenon of is a chemical reaction between hydroxide ion, in the form of Sodium or Potassium Hydroxide, found in Portland cement and occur in some types of aggregates in the concrete; water, as one of the main components of concrete, acts a catalyst in the reaction, and causes the reaction speed to increase [3]. Warm and humid climates and wet structures, such as concrete dams, provide the best conditions for the occurrence and advancement of this phenomenon [4]. This reaction causes expansion, cracks [1], color-change of the concrete surface, unusual displacements, and disruption of the functioning of the facilities and equipment attached to the dam [4]. The most important structural effect of AAR is the creation of strain in concrete that is caused by expansion of concrete due to the formation of material such as silicate gel in the reaction. The magnitude of this expansion depends on temperature, moisture, the reactivity of aggregates, and the stress in the structure. Also, concrete properties, including its elasticity module and tensile strenght are reduced during the reaction [3].

Here we point to some similar studies performed in this regard inside and outside Iran. Moshtagh Kahnamooi and Ghaemian (2003) [5]: used two models for evaluating AAR in concrete dams using the finite element method. Results of isothermal and non-isothermal analyses of one of the gravity dams at Beauharnois power plant using both models and the displacements obtained were compared with the measured values.

Lame and Mirzabozorg (2014) [4]: first used a structural behavior of concrete dams simulation software based on the expanded finite element method, using one of the available powerful phenomenological models, and the modeling capability of the structural effects of the reaction in 3D space. Then, in order to analyze the effect of this phenomenon on concrete dams, used the Karaj dam as a case study and required static time analyses were performed on it.

Huang and Pietruszczak (1999) [6]: used a nonlinear continuum theory for thermo mechanical modeling of concrete exposed to Alikali-Silica Reaction (ASR). Then numerical samples were suggested for evaluating the proposed formulation. Specifically, the model was used for analyzing the various structural elements of the Beauharnois power plant in Quebec, Canada.

Saouma and Perotti (2005) [7], [8]: proposed a structural model for AAR in structures, parametrically for evaluating the model, and ultimately using it as an actual 3D structure. Finally, the model was used for evaluating the long-term response of arch gravity dam.

In the present paper, one of the gravity dams at Beauharnois power plant has been studied and is analyzed using ANSYS 13 software assuming that AAR does not occur. Then the dam with the case that is analyzed considering AAR, the results were evaluated and compared. Results, including displacements are very different.

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II. First Case(Assuming AAR Does Not Occur)

The dam is analyzed in this condition (assuming no AAR occurs). The analysis was performed over 50 years with monthly time steps. The loads considered were the weight of the dam structure and the hydrostatic pressure on it. Temperature variations were applied as follows [9]:

The air temperatures at the dam location were considered, according to the works of Mr Leger et al. (1993). The lowest daily temperature was 14.92 ℃ and the maximum daily temperature was 18.12 ℃. To simplify the model, only the effects of convection and radiation were considered; the effects of thermal flux from sources, like the sun, were ignored. The temperature of the water reservoir was based on the works of Mr. Zhu Bofang, and the temperature of the adjacent fondation node is assumed to be constant and equal to 6.2 ℃. Other temperature parameters are as follows [9]:

Thermal conductivity: 2.62 N//sC0
Specific heat capacity: 912 m2/s2C0
Convection coefficient: 23.2 N/msC0
Radiation coefficient: 4.2 N/msC0

For taking into account both the convection and radiation effects, the sum of the radiation and convection coefficients was considered in the model.

III. Second Case(with AAR)

In this condition the dam is analyzed with the effects of AAR. Considering that the dam is about 50-years-old, it was assumed that only 25 years have passed since AAR (accure of the reaction in the second half of the dam's life time), The period under analysis is 50 years with monthly time steps [10]. The loads considered, the temperature variations, and temperature parameters are identical to the first case.

The Leger model was used. This model was proposed in 1996, and in this model, the foctors of temperature, moisture, reactivity of constitiuents, and stresses in concrete are used to calculate the strains caused by AAR. The Leger model is a simple, comprehensive, and non-kinetic phenomenological model [10].

A. Modeling AAR

As mentioned before, the selected model is the Leger model (1996). This model is used as follows [10]:

The strain caused by AAR (whose parameters are weight factors) is equal to:

$$\varepsilon_{AAR} = \left[F_\sigma . F_T . F_M . F_R\right] \tag{1}$$

where (F_T,$F\sigma$) are the effects of temperature and stress, and the two weight factors are the reactivity of aggregates and moisture (F_R, F_M), which are considered to be constant (and equal to one) throughout the body of the dam. The strain due to the reaction is as follows:

$$\varepsilon_{AAR} = F_\sigma \times F_T \tag{2}$$

where $F_\sigma$is used for considering the effects of stresses of applied pressure in reducing the strains caused by the reaction, and the increasing effect of tensile stresses are ignored.

$$\begin{cases} F_\sigma = 1 if \sigma \rangle 0 \\ if \sigma \le 0 \to \sigma_{abs} = abs(\sigma) \Rightarrow \end{cases}$$
$$\begin{cases} F_\sigma = 1 - K_1 \log \dfrac{\sigma_{abs}}{\sigma_L}, \sigma_L \le \sigma_{abs} \le \sigma_{\max} \\ F_\sigma = 1 if \sigma_{abs} \langle \sigma_L \end{cases} \tag{3}$$

σ_L is the compressive stress, at which stresses lower than that, strains are considered free and equal to strain without any compressive stress. σ_{max} is the compressive stress, at which stresses above that strains are considered equal to zero. σ is the average of the main stresses, and σ_{abs} is the absolute value of σ. (K_1=0.701، σ_{max} =8mp، σ_L =0.3mp)

For obtaining F_T at different points on the dam, using the results of thermal analysis of every month at the desired point in each of these months as a weight factor F_{Ti}=(x,y,z)is obtained as follows:

$$\begin{aligned} &T_i(x,y,z)\langle T_L \to F_{Ti}(x,y,z) = 0 \\ &T_i(x,y,z)\rangle T_L \to F_{Ti}(x,y,z) = \frac{T_i(x,y,z) - T_L}{T_{\max} - T_L} \end{aligned} \tag{4}$$

At low temperatures, the function inclines toward zero, and at high temperatures inclines toward one. Considering the fact that AAR stops at low temperatures, Here, T_L is known as the boundary temperature, which according to experts is considered to be 10 ℃, and the value of T_{max} is obtained from the maximum yearly node temperature.

The total strain is equal to:

$$\varepsilon_0 = \underbrace{\varepsilon_{AAR}}_{AAR.expansion} + \underbrace{\varepsilon_T}_{thermal.srtain} \tag{5}$$

Here, from the changes in concrete properties, only the effect of AAR on reducing module elasticity is considered. In this model, this follows the following linear equation:

$$E = E_0(1 - K_2 t) \tag{6}$$

K_2 coefficient is selected such that the value of module elasticity after 25 years since the reaction, and the 50-year analysis period, reaches 80% of the original amount (K_2 =0.004) [10].

IV. The Dam Under Study

Fig. 1 shows one of the gravity dams at Beauharnois power plant in Quebec, Canada, And about 50 years have passed from the age of this dam. The reason this dam was chosed for analysis is that signs of AAR are seen in the structure [9]. For modeling the dam, the 4-node strain flat element with element size of 1 meter and 278 knots was used.

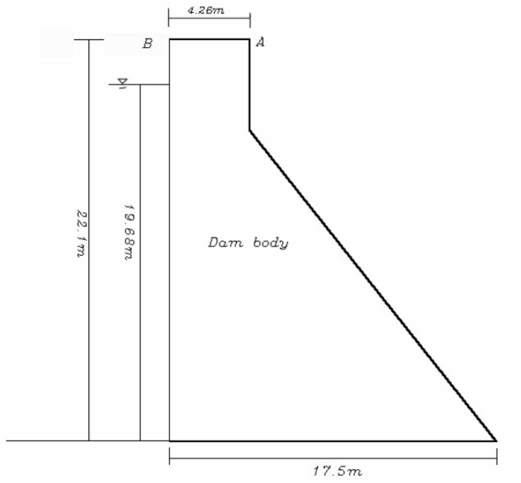

Figure 1. Transverse profile of the dam [3]

V. Result of Analyzing Both Cases

Fig. 2a and Fig. 2b show the contours of horizontal and vertical displacements of the dam, assuming no AAR, after the 50-year analysis period. Next to them are vertical and horizontal displacements contours of the dam, after 25 years of reaction shown in Fig. 3a and Fig. 3b. These contours indicate the distribution of displacements in the dam.

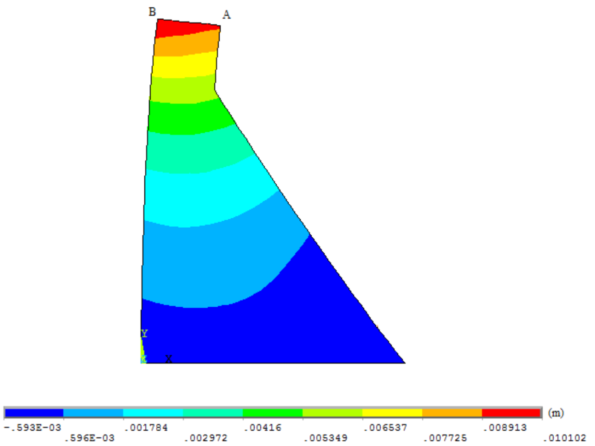

Figure 2a. Horizontal displacement contours assuming no AAR occurs

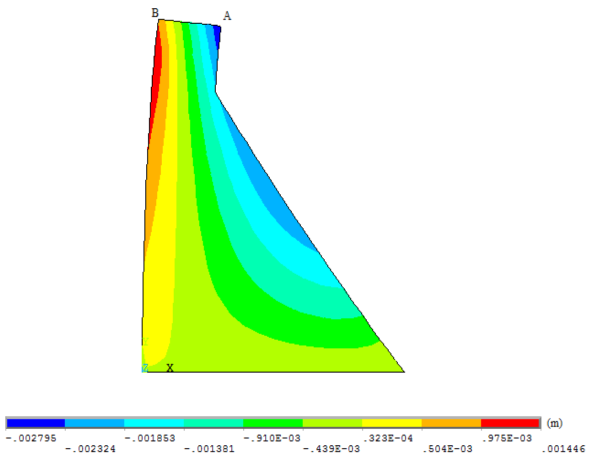

Figure 2b. Vertical displacement contours assuming no AAR occurs

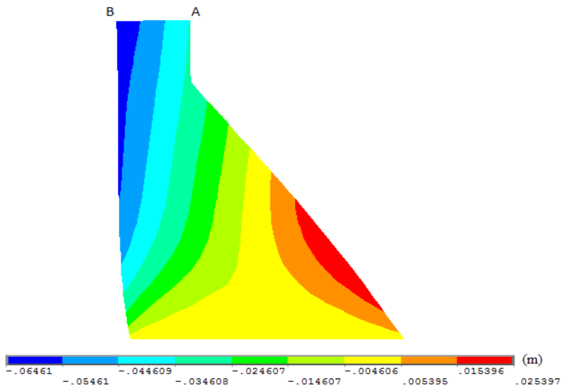

Figure 3a. Horizontal displacement contours after 25 years of reaction[10]

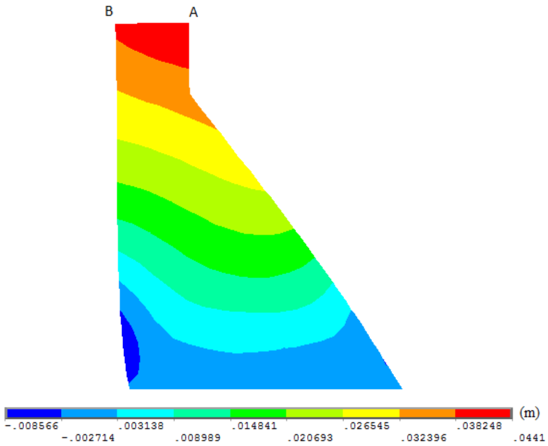

Figure 3b. Vertical displacement contours after 25 years of reaction [10]

VI. Analysis Result-Comparison from the Two Cases

Since the two cases considered have similar settings, except the presence of AAR, the differences in the responses obtained in the two cases is just due to effect of AAR. Table I shows the values of the final displacement of points A and B (in the dam crest–Fig. 1) in the two cases considered and offers a comparison. Furthermore, since the dam is in fact exposed to AAR, the measured values are given for comparison and correctness.

As we can see from the above table, the reaction has had a considerable effect on the Structural response. In other words, when not considering the effect of AAR, the structure does not have a noticeable displacement relative to the case with AAR. In the case without considering AAR, the dam gets directed down stream, because in this case, the dam is directly influenced by the thermal strains caused by temperature variations and the displacements caused by thermal strains direct the dam down stream; where as in the other case, the dam has moved up stream (the reservoir) under effect of AAR.(As shown in their displacement contours). And, the values measured in the actual case, in comparison with the first case, show a large difference, and show little difference with the second case.

TABLE I. COMPARISON OF THE FINAL DISPLACEMENTS OF POINTS A AND B IN BOTH CASES; AND WITH THE MEASURED VALUES

Point	Horizontal displacement (cm)			Vertical displacement (cm)		
	consider-ing without AAR	With AAR	Measured Valuse	consider -ing without AAR	With AAR	Measured Valuse
A Downstream	0.908	-3.44	-3.22	-0.28	4.41	4.88
B Up stream	1.01	-6.46	-	0.09	4.03	3.31

VII. CONCLUSION

In this paper, the dam was analyzed assuming no AAR occurs; then the case of dam was expressed that was analyzed with the reaction; and finally the results of the phenomenon in the design or the repair of such structures first and second case were analyzed and compared. Results indicate the considerable effect of AAR on the structural behavior of the dam, including displacements in the dam that have occurred mostly in the upper parts and near the crest of the dam. The results from this study indicate the importance of Alkali- Aggregate Reaction on the structural behavior of concrete dams, such that these unusual displacements can have a big effect on the performance of the facilities and equipment attached to the dam. This reaction can continue throughout the life of the dam and influence the utility of the structure in the long run; finally the importance of modeling phenomenon in the design or the repair of such structures this is shown. Modeling this reaction is necessary in the analysis of concrete dams. At the end, suggested for further study, using the other numerical models in this field and analysis of the more results such as stress and crack.

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