Proceedings of International Structural Engineering and Construction, 7(2), 2020
Emerging Technologies and Sustainability Principles
Edited by Askarinejad, H., Yazdani, S., and Singh, A.

ISSN: 2644-108X
www.doi.org/10.14455/ISEC.2020.7(2).STR-45

A SLOT-CUTTING TECHNIQUE FOR REPAIR AND REHABILIATION OF CONCRETE DAMS AFFECTED BY ALKALI-SILICA REACTION

MOHAMMAD S. POURBEHI and JAVB STRASHEIM

Dept of Civil Engineering, Stellenbosch University, Stellenbosch, South Africa

The combined impacts of earthquake damage and aging of concrete material on vulnerable aged dam systems have been typical causes of structural failure. The possible malfunction or loss of these vital systems and components can have serious socio-economic consequences and impacts on potable water resource availability, crop irrigation, and electric power generation. Worldwide extensive work has been done to evaluate the structural safety of aged concrete dam system components and to develop suitable remedial action and rehabilitation strategies. This paper reports a Chemo-Thermo-Mechanical Finite Element model developed by the authors which was used to demonstrate the use of the Finite Element Method (FEM) to model the behavior of a synthetic dam if the concrete is affected by Alkali-Silica Reaction (ASR), applying the slot cutting rehabilitation technique. ASR is a destructive chemical reaction between the cement paste and siliceous aggregate components in concrete materials that causes long-term expansion and degradation of concrete structures, including dams. Slot cutting is recognized as one of the promising techniques suitable to repair concrete dams suffering from ASR. The results show that the FE model could predict the stress and displacement field before and after the sawing of the slot in an assumed dam affected by ASR and demonstrate a promising capability for modeling the repair strategies in real dams suffering from ASR.

Keywords: Concrete expansion, Repair techniques, Finite element method, DC3D4.

1 INTRODUCTION

Extensive research has been done during the last two decades on dams subjected to Alkali-Silica Reaction (ASR). This research has led to the advancement of model formulations in the study of a number of aspects of the effect of expansive chemical reactions on concrete structures. The number of documented dam structures affected by ASR has been increasing in the recent past. In some cases, rehabilitation protocols including structural repair techniques were implemented. However, a number of dams still needed to be decommissioned (Pourbehi *et al*. 2018, Sellier *et al*. 2017). The literature indicates that the ASR impacts relate to the dam location as well as to the physical layout of the dam. Operational and structural integrity risks specifically relating to typical dams under investigation can be formulated. The appropriateness and effectiveness of remedial actions depend on a variety of parameters, such as the type of the dam; order of magnitude and rate of the mass concrete dilation; local environment conditions; and longer term material viscoelastic behavior, which includes creep and relaxation. Installed ancillary mechanical and other equipment and foundation geological configurations also impact remedial actions for some dams. The reduction of the level of compressive stresses in the structural and mass concrete by the use of a slot cutting technique has already been used for a number of dams. It can be expected that there will be a growing demand for this technique because of the amount of dams impacted by ASR (Metalssi *et al*. 2014). To efficiently release the compressive stresses and effectively relieve the level of built up stress at the dam support structural components, a distinct number of cuts have been made in the longitudinal direction of affected dams for some cases. In other cases, inserting cuts in areas of localized stress concentration seemed to have met with success (Sims and Poole 2017). It can be stated that implementation of this technique, which is not accompanied by a long-term surveillance program and numerical modeling, may lead to the occurrence of undesirable side effects, such as uncontrolled deformations in adjacent concrete and equipment due to the ASR (Gocevski and Yildiz 2017). The modeling of repair and rehabilitation strategies for dam in the real world was not in the scope of the research reported here. However, the capabilities of the FEM techniques developed as part of the study are demonstrated using a FE code developed by the authors (Pourbehi *et al*. 2019). In this research, this technique was used in the modeling and analysis of slot cutting applied to a hypothetical model dam that is assumed to be affected by ASR.

2 NUMERICAL STUDY ON THE USE OF SLOT CUTTING IN A HYPOTHETICAL DAM

The geometrical layout and configuration of the assumed dam are shown in Figure 1. In this figure, a cut with thickness $e_{sc} = 10\,mm$ at point A is shown. Metalssi *et al.* (2014) states that the dimensional thickness range of the slot cuts used in typical current industrial applications varies between 10 to 20 mm. An initial constant material temperature of 8 ℃ is assumed in the interior of the dam wall and upstream and downstream wall surface temperatures of 8 ℃ and 20 ℃, respectively, are used. The gravity loads and hydrostatic loads due to the water at the upstream surface of the dam are included in the model. The applicable properties of the concrete material of the dam and the ASR model parameters used are listed in Table 1. A standard linear elastic analysis is performed. The applicable global X, Y, and Z coordinate directions are shown in Figure 1.

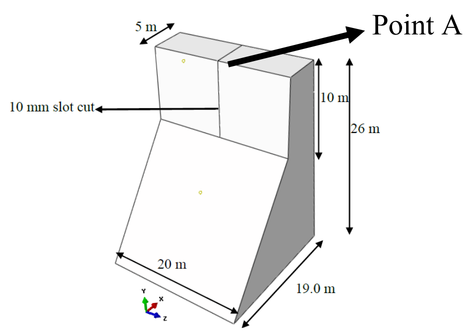

Figure 1. Dimensions and global coordinate system of the hypothetical dam with a 10 mm slot cut.

2.1 Finite Element (FE) Simulation of the Hypothetical Dam

Initially, a transient thermal analysis is performed. The results of this analysis, which, in this case, spans over a period of 20 years, is used to set up the thermal gradient data to be used in the subsequent Alkali-Silica Reaction (ASR) analysis. Three-nodded (DC3D4) tetrahedral elements formulated and implemented for FE heat transfer and transient thermal diffusion analysis are used in the model. The mesh consists of 37611 elements. Gap finite elements are incorporated in the mesh to define a surface-to-surface contact region and to model and analyze the contact problem associated with the process of the closure of the slot as cut in the material. The analysis results, which include ASR strain data as well as displacement and stress values obtained in the model at Point A, are illustrated in in Figure 1.

Table 1. ASR model parameters and material properties of concrete used in the numerical modeling.

E_c (GPa)	ν	ρ (kg/m^3)	τ_l (day)	τ_c (day)	β (%)
Young's Modulus	Poisson's ratio	Density	Latency time	Characteristic time	ASR material dilatancy
30	0.2	2400	200	80	0.20

3 RESULTS OBTAINED AND DISCUSSION OF RESULTS OBTAINED

The results for the transient thermal FE analysis are shown in Figure 2. Contour diagrams for the two time periods used i.e. 5 and 20 years are indicated. In these figures, the diffusion of the surface heat from the downstream face of the dam into the interior of the dam can be seen. Pourbehi *et al* (2018) showed that the level of ASR is strongly linked to the temperature in the solid material. The spatial and temporal variations of the temperature levels in the dam cause the activation of varying levels of the ASR mechanism. Higher temperatures lead to an increased rate of the ASR.

Figure 2. Variation of the temperature along the dam wall in Kelvin after a) 5 years and b) 20 years.

Figure 3 shows a contour plot of the ASR reaction extent after time periods of 5, 10, and as well as 20 years. It can be observed that the reaction extent is in the order of 96.8% at point A after 5 years. The vertical strain at point A in the dam model, before the slot cutting is applied, is indicated in Figure 4. As shown, the ASR induced strain approaches a maximum value of 0.08% after 6 years and remains constant for the remainder of the analysis. The vertical displacement of the dam amounts to 5 mm after a 5 year period. The maximum value of the displacement of 11.5 mm is reached after a period of 20 years of ASR activity.

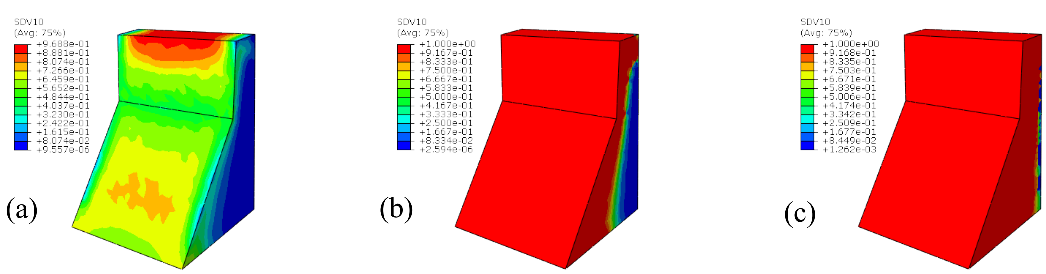

Figure 3. History of the kinetic of the reaction in the dam body before slot cutting after a) 5 years, b) 10 years, and c) after 20 years.

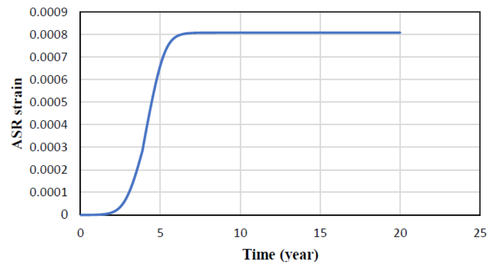

Figure 4. History of the ASR strain of Point A in the vertical direction without slot cutting for a period of 20 years.

The effect of the degradation of the material is taken into account in the FE model by use of a damage variable (FV1). A contour plot representation of the values for this parameter is shown in Figure 5 after a time period of 20 years has elapsed. It can be seen in Figure 5 that the ASR damage variable value reaches 26.4% after 20 years. The concrete material of the dam wall has thus experienced a 26.4% E-Modulus reduction from its initial value. The reduction in the value of the Young's modulus leads to an estimated residual value of E=22.1 GPa after 20 years.

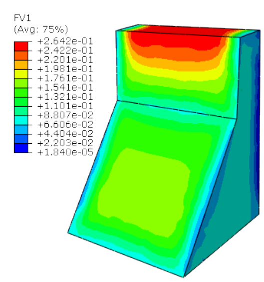

Figure 5. Contour plot of the field variable (FV1), which shows the current ASR damage extent in the dam.

Figure 6 shows the transverse displacement (U3) for point A in the global Z direction after a time period of 20 years has elapsed. The cut for the slot is made after 4.8 years, and the impact of this on the ASR-induced stress state in the material of the dam is studied. It can be concluded that the slot, which was cut, closes due to the instantaneous release of the initial compressive stress. The analysis import and phasing technique, which is available in the Abaqus FE software (Simulia 2016), was used in this phase of the analysis. Figure 7 contains a contour plot of the transverse displacement (U3) of the dam for a point in time 5.2 years after the slot was introduced. The plot confirms that the slot cut has remained closed after it was made. Due to the symmetry, the opposite side of the slot also exhibits a movement of 5 mm.

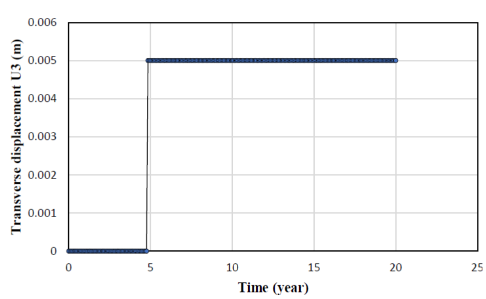

Figure 6. Time variation of the movement in the transverse direction (U3) at Point A.

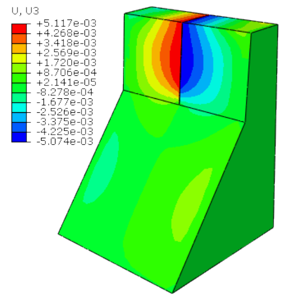

Figure 7. Contour plot of the displacement (U3) in the transverse direction after 20 years.

Figure 8 shows the value of the compressive stress (S33) in the global Z direction at Point A in the dam before and after the slot cutting is implemented. The dam without a slot displays stress level increases with time. A maximum value of compressive stress of 17 MPa is reached. The value obtained from the model can be cross-checked using an estimate based on the maximum-computed theoretical value of the stress: $E_c \,.\, \varepsilon_{t=20}^{asr}$. The Young's modulus of the material is E_c=22.1 GPa. The modulus value is reduced by the ASR damage variable (d_{asr}), which is coupled to the ASR expansion. This leads to a strain level of $\varepsilon_{t=20}^{asr} = 8.0 \times 10^{-4}$. Refer to Figure 4, which shows the change of the strain level with time. Figure 8 applies to the dam where a slot is cut 4.8 years after the model simulation commenced. The stress level is reduced when the cut is made. The level then gradually increases in value until it stabilizes later at a level of compressive stress of 6.5 MPa.

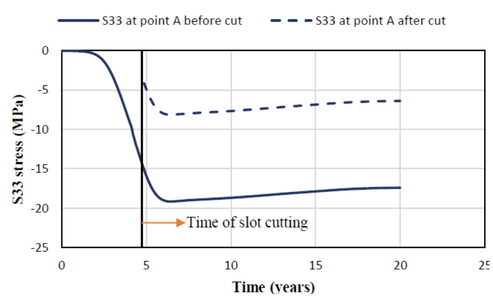

Figure 8. History of the compressive stress at point A in a transverse direction for the reference dam before and after the slot is cut.

This compressive stress value computed is in agreement with the theoretically computed level of stress in the global Z direction for the dam as calculated by Eq. (1):

$$\sigma_{33} = E_c . \varepsilon_{t=20}^{asr} - E_c . \frac{e_{sc}}{L} = 6.63 \text{ MPa} \tag{1}$$

In Eq. (1), L is the length of the dam. In this case, the length is 20 m. By comparing the computed stress with the stress values of the dam model with the slot, it can be deduced that the developed ASR FE model can effectively simulate the effects of the process of slot cutting on the model hypothetical dam. By using the indicated material parameters and the stress state in the dam before and after the slot cut, the effect of the slot cut on the ASR induced stresses in the dam can be determined. The following conclusions about this FEM study of the hypothetical dam with the 10 mm slot cut at the midpoint of the crest of the dam can be made:

- It could predict the variations of the level of the strain field and the displacement of the dam suffering from ASR.
- It predicts the degradation of concrete material due to ASR with acceptable accuracy.
- It can be used to estimate the stress levels before and after slot is cut in the dam.

4 CONCLUSION

A number of intervention strategies exist to deal with dams affected by ASR. Slot cutting is recognized as one of the most promising strategies and has been applied with success to some dams in the real world. This paper described a model that can simulate the onset of ASR using a Chemo-Mechanical FE technique coupled with the slot cutting technique. In this case, it was implemented for a hypothetical dam structure. Parameters, including temperature variations, non-uniform time dependent material degradation, and the effect of confining stress levels, were taken into account in the model and analysis. The model predicted the ASR strain levels and displacements fields, material deterioration effects, and as well as the important stress state in the dam before and after slot cut closure with reasonable accuracy. The results obtained also agreed well with the values based on theory and solid mechanics formulations. The theoretical approach used to compute the levels of the stress state associated with the slot cut was in good agreement with the values determined using the model described. In closing, it needs to be noted that modeling slot cuts in an actual dam affected by ASR is a complex process. Great care needs to be exercised in the planning and implementing of any slot cutting remedial program for a real world dam structure.

Acknowledgment

The authors wish to acknowledge the funding provided by Institute of Structural Engineering at Stellenbosch University supporting this research.

References

Gocevski, V., and Yildiz, E., *Numerical Analysis of AAR Affected Structures with Slot Cuts*,. in *Swelling Concrete in Dams and Hydraulic Structures*, Sellier, A., Grimal, E., Multon, S., and Bourdarot E., (eds.), 188–202, Wiley, First Edition, 2017.

Metalssi, O., Seignol, J., Rigobert, S., and Toutlemonde, F., *Modeling The Cracks Opening-Closing and Possible Remedial Sawing Operation of AAR-Affected Dams*, *Engineering Failure Analysis*, 36, 199–214, https://doi.org/10.1016/j.engfailanal.2013.10.009, 2014.

Pourbehi, M. S., van Zijl, G. P. A. G., and Strasheim, J. A. v. B., *Modelling of Alkali Silica Reaction in Concrete Structures for Rehabilitation Intervention,* in ICCRRR2018, F. D., Alexander, P. M. M.G., Beushausen, H., (eds.), 199, Cape Town, https://doi.org/https://doi.org/10.1051/matecconf/201819903007, 2018.

Pourbehi, M. S., van Zijl, G. P. A. G., and Strasheim, J. A. v. B., *Analysis of Combined Action of Seismic Loads and Alkali-Silica Reaction in Concrete Dams Considering The Key Chemical-Physical-Mechanical Factors and Fluid-Structure Interaction*, Engineering Structures, 195, 263–273. https://doi.org/10.1016/j.engstruct.2019.05.087, 2019.

Sellier, A., Grimal, E., Multon, S., and Bourdarot, E., *Swelling Concrete in Dams and Hydraulic Structures: DSC 2017* (First edit). ISTE Ltd, UK, London. Retrieved from https://www.wiley.com/en-gb/Swelling+Concrete+in+Dams+and+Hydraulic+Structures%3A+DSC+2017-p-9781119448891 on 2017.

Sims, I., and Poole, A., *Alkali-Aggregate Reaction in Concrete: A World Review*, CRC Press, London, UK, 2017.

Simulia, *Abaqus 2016 Theory Guide,* Dassault Systemes, 2016.