Seismic Analysis of the Kleinplaas Dam Affected by Alkali-Silica Reaction Using a Chemo-Thermo-Mechanical Finite Element Numerical Model Considering Fluid Structure Interaction

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Abstract

Alkali Silica Reaction (ASR) is a long term chemical reaction causes swelling and damage to the concrete material in the form of cracking and material deterioration. In this research a chemo-thermo-mechanical ASR finite element numerical code is developed to model and analyse this phenomenon in concrete dams. It considers the effects of variables such as temperature, humidity, non-uniform time-dependent material degradation and 3D stress confinement on ASR evolution. While the structural behaviour of ASR affected structures under monotonic and quasi-static loading has been extensively investigated over the last decades, limited research has addressed the effect of dynamic loads on structures affected by ASR. The combined effect of old and new cracks under dynamic excitation may cause dam failure. The SU-ASR (Stellenbosch University ASR FE code) model developed, is used to analyse and predict dynamic behaviour of the Kleinplaas dam which is located on the Jonkershoek River near Stellenbosch in the Western Cape province of South Africa. The combined ASR and seismic actions based on the state of the structure at the end of the long-term ASR analysis are investigated and comparisons are made through a comprehensive study of the damage development and crest displacement. The development of the cracks in the coupled analysis of the ASR and seismic load is significantly different from the cracks in the dam when only ASR is considered.

1. Introduction

ASR is a deleterious chemical reaction between certain siliceous aggregates and with the alkalis that are available in the cement, which typically leads to the formation a gel product. This reaction causes an increase in the molar volume of the gel product and depending on the micro porous structure of the concrete material, introduces a build-up of pressure in the material. At first, this pressure is relieved by the gel filling the voids, micro cracks and pores of the concrete matrix. Once there is no more space, expansion occurs that may lead to cracking if the tensile cracking strain limit is reached.

Factors that can influence the likelihood, rate and severity of the ASR expansion and/or resulting deterioration and damage include: alkali availability, aggregate constitutive properties, environmental conditions including moisture (relative humidity), temperature, confining stresses and mechanical loads.

An increase in the alkali concentration in the pore solution and especially the ratio of reactive silica to alkali play a significant role in swelling of concrete material due to ASR. Results of experiments indicate an increase in pH due to increase in the alkali concentration in the pore solution of concrete material (Dyer 2014).

Two main categories of aggregates are found, namely early reactive and late reactive, manufactured from rocks that contain specific types of minerals. Alaud and van Zijl (2017) studied the ASR effects on two types of aggregates that are widely used in South African construction namely Granite and Greywacke. They pointed out that concrete samples made using the Greywacke aggregates show late expansive behaviour, but the ultimate expansion was significantly more than that of the samples made using Granite aggregates. Also, the reduction in elasticity modulus (E-Modulus) for the samples with Greywacke aggregates was more than that of the Granite aggregates.

The ASR gel is highly hydrophilic and when water as solvent agent enters the medium this results in gel expansion. Thus, the extent to which expansion occurs is dependent on the amount of water available within the concrete. In addition, the humidity of the air surrounding the concrete could affect the expansion. Experiments on the role of relative humidity in ASR expansion show that a relative humidity below roughly 75% ASR cannot produce significant expansion (Dyer 2014; Multon et al. 2009; Steffens et al. 2003).

The ASR reaction is strongly influenced by temperature. In the temperature range of about 20 to 40°C the swelling increases with the increase of temperature. ASR is a thermo-activated process and thermal conditions of the concrete structure should be considered in a numerical model of the process (Ulm et al. 2000; Dyer 2014).

ASR can be described as two simultaneous but uncoupled processes: The production of expansive silica...
gel, and its mechanical consequences. In addition, mechanical stress could affect both processes (Morenon et al. 2017; Multon and Toutlemonde 2006). Indeed, some chemical reactions and dissolution processes are known to be hindered or promoted by external pressure. However, the results from Larive (1998) indicate that such phenomena do not occur in ASR, at least in the range of stresses encountered in the field. To the contrary, in a recent experimental research by Liaudat et al. (2018) it has been shown that a 3D state of permanent hydrostatic compression stress of about 9.7 MPa can hinder the development of ASR volumetric strains. Mechanical loads also affect the fracture processes in the material, and therefore the expansion as it is, in ASR, may be strongly coupled with internal damage (Gioria et al. 2015).

Furthermore, material degradation may significantly change the seismic behaviour of the concrete structures such as dams, and it is also necessary to predict the seismic safety of e.g. dams suffering from ASR considering the time dependent material deterioration. Research has been performed on aged concrete dams assuming a uniform material time dependent degradation index along the dam body, due to physical and chemical attacks such as freeze-thaw cycles and fatigue and expansive chemical reactions (Nayak and Maity 2013; Valliappan and Chee 2009). However, using a uniform material degradation index for the dam structures as a whole may lead to an overestimation of the structural dynamic response and the dynamic behaviour of the damaged structure.

In general, numerical models for modelling ASR and its effects fall into three main categories: (1) macro-structural models concerned with the analysis of structures affected by the reaction (Capra and Sellier 2003; Charlwood 2009; Li and Coussy 2004; Saouma and Perotti 2006; Steffens et al. 2003; Ulm et al. 2000); (2) microstructural models that link the chemical reaction to its impact at the material level (Bazant and Steffens 2000; Lemarchand et al. 2002); and (3) mesoscopic models used for analysis of the ASR mechanism (Comby-Peyrot et al. 2009; Dunant and Scrivener 2010). Anisotropy can be explicitly represented in these mesoscopic concrete models that consider the multi-phase behaviour of aggregate, cement paste, voids and ASR gel products.

An ASR computational model that considers several profound phenomena and factors as discussed in the introduction is elaborated in this paper, and applied to the Kleinplaas Dam in South Africa. The response of the affected dam to a seismic event of magnitude expected in the regions, after several decades of ASR deterioration, is subsequently investigated.

2. Modelling approach

In this section the solid mechanics based mathematical formulation of ASR is presented. To correlate the material degradation with the material expansion due to ASR, various parameters are incorporated in the model. These include temperature effects, kinetics of the reaction, characteristic time scales, 3D state of the stress and confining effects and non-uniform time dependent material degradation. Also, anisotropy of the ASR swelling in principal directions is considered using a weighting function in terms of the 3D state of stress. Subsequently, a mathematical description of all the phenomena involved in model is presented.

2.1 ASR constitutive modelling

In this research, it is assumed that the strain due to ASR is volumetric in nature in configurations without confining stresses. This assumption is considered by many researchers and experimental works demonstrated a reasonable agreement with numerical models considering volumetric strain (Multon and Toutlemonde 2006; Saouma and Perotti 2006). In recent experiments by Liaudat et al. (2018), an ad-hoc device, which is able to apply triaxial loads on ASR specimens for a long period of time, is introduced. The results indicate that the ASR expansion is volumetric in free stress state tests and transfers to the less compressed direction for configurations where confining stresses are present. Also, they observed that a triaxial compressive stress state equal to 9.7 MPa could hinder the volumetric strain rate. Therefore, a refined model from Saouma and Perotti (2006) to estimate the expansion from ASR strains in each principal direction can be defined by a rate form equation that is suitable for integration:

$$\dot{\varepsilon}_{asr}^{mv} = \Gamma_{asr}(\sigma_v)\dot{\varepsilon}(\tau_v, \sigma_v, \beta W_{asr}(\sigma_v)$$

where $\xi \in [0,1]$ represents the extent of the chemical reaction, as function of characteristic time $\tau_v$ and latency time $\tau_c$, which can be estimated using an Arrhenius relation. $\tau$ represents the temperature, and $\sigma_v$ is an expression of volumetric stress. $\beta$ is the asymptotic volumetric expansion strain in a confinement-free experiment, which can be estimated from characterisation data according to the aggregate type, moisture content and other mix proportion parameters (Ulm et al. 2000). $W_{asr}(\sigma_v)$ is introduced as a weighting function in equation (1) for the purpose of the distribution of ASR volumetric strain as a function of stress in each tensorial principal direction (i.e., $i = 1, 2, 3$). The effect of confinement stress on ASR expansion is considered through a reduction function defined as:

$$\Gamma_{asr} = \begin{cases} 
1 & \sigma_v \geq 0 \\
1 - (\sigma_v/\sigma_v')^\beta & 0 \geq \sigma_v \geq \sigma_v' \\
0 & \sigma_v < \sigma_v', 
\end{cases}$$

where $\sigma_v'$ is a limit below which ASR could be suppressed by confining pressure. In this research, it is assumed that $\sigma_v'$ is equal to 9.7 MPa, based on findings of Liaudat et al. (2018).

A further concern about the concrete material affected
by ASR is that of concrete deterioration. Equation (3) uses an ASR damage factor, which basically is a function of ASR expansion, to determine the deterioration of the concrete E-Modulus and tensile strength $f_t$, which is a time-dependent function (Capra and Sellier 2003):

$$
E = E_0 (1 - d_{asr})
$$

$$
f_t = f_{t0} (1 - d_{asr})
$$

where $E_0$ and $f_{t0}$ are the initial Young’s modulus and tensile strength respectively. During the ASR process, the swelling gels penetrate the concrete matrix and induce cracking of the aggregates and the surrounding cement paste. The damage of the material leads to elastic stiffness degradation. The ASR damage factor, $d_{asr}$, may be linked to the expansion strains from the experimental results as shown in Fig. 1 (ISE 1992). Furthermore, according to the experimental results, equation (4) is used to determine $d_{asr}$, using the maximum ASR expansion strain in the principal direction (Capra and Bournazel 1998):

$$
d_{asr} = 1 - \frac{E}{E_0} = \frac{\max(\varepsilon_{asr}^{\text{max}})}{\max(\varepsilon_{asr}) + \beta}
$$

The evolution of damage is also shown in Fig. 1.

### 2.2 Numerical model implementation

The coupled problem of heat diffusion and thermo-activated ASR kinetics is approached by initially doing transient thermal analysis with initial boundary conditions. This requires a number of parameters, among them: 1) the air temperature variation; 2) the spatial and temporal (at least 12 or 24 increments a year) variation of the water temperature which is required; 3) the dam reservoir level variation during a typical year; 4) the concrete thermal properties. For this analysis, and the subsequent stress analysis, an analysis time unit or time increment, is defined. The flowchart in Fig. 2 summarises the steps required to implement the numerical model. This model is implemented using the developed subroutines in a sequentially coupled multi-physics analysis technique at Stellenbosch University (SU), in the ABAQUS finite element package (Simulia 2016). This model is now referred to as the SU-ASR model. See Figs. 2 and 3 for more detail of the proposed model.

The concrete mechanical behaviour is modelled with concrete damage plasticity (CDP) by Lee and Fenves (1998) implemented ABAQUS. By strain decomposition, the stress rate vector is expressed by,

$$
\sigma = (1 - \phi)\sigma_{\text{SD}} + (1 - \phi)D_i^0 (\varepsilon - \varepsilon^{pl} - \varepsilon^{th} - \varepsilon^{asr})
$$

where $D_i^0$ is the initial stiffness matrix, and the total, plastic, thermal and ASR strain vector components are denoted by $\varepsilon$, $\varepsilon^{pl}$, $\varepsilon^{th}$ and $\varepsilon^{asr}$ respectively. The thermal strain is determined from the thermal coefficient $\alpha$ and the temperature increment. The level of damage ($\phi$) is defined as:

$$
\phi = 1 - (1 - d_{asr})(1 - d_m)
$$

where the mechanical damage ($d_m \in [0,1]$) is defined by linear softening. Full details of the ASR constitutive model and computational implementation is given in (Pourbehi 2018) and (Pourbehi et al. 2019).

Fluid-Foundation-Structure Interaction (FFSI) also has received much attention in Finite Element Analysis (FEA) of dams. These techniques include the effects of hydrodynamic pressure on the dam-water interface, and assumed boundary conditions on the fluid domain, such as far-field non-reflective and the admittance boundary condition for modelling the sediments in the reservoir bed.

The hydrodynamic pressure induced in the reservoir, which exceeds the hydrostatic pressure during motions of small amplitude, is governed by the Helmholtz equation (Zienkiewicz 2006):

$$
\nabla^2 P = \frac{1}{C_0} \frac{\partial^2 P}{\partial t^2}
$$
where $P$ is the hydrodynamic pressure, $t$ the time and $C_s$ the acoustic wave speed in water. The FFSI system comprises boundary conditions for the upstream dam face, non-reflecting radiating boundary, admittance (sediment layer) and free surface boundary condition.

3. Numerical modelling of Kleinplaas dam affected by ASR

For the purpose of the further validation of SU-ASR FE code developed in this research, Kleinplaas dam is chosen to perform an FE analysis to compute the ASR expansion and subsequent material disintegration and cracking in the wall of the dam.

3.1 Dam configuration and material properties

Kleinplaas dam is a balancing concrete gravity dam located in the Jonkershoek River near Stellenbosch in the Western Cape province of South Africa. See Fig. 4. The dam was constructed in 1982 and evidence of swelling, cracking and material degradation was observed in 1991 during a dam safety investigation carried out by Department of Water and Sanitation (DWS 2009). Greywacke aggregates of the Malmesbury Group from a quarry in the Western Cape area, which are intrinsically alkali-reactive (Alaud and van Zijl 2017), were used in the concrete for construction of the dam. This is deemed to be the main contributing factor to the ASR encountered in the Kleinplaas dam. Thereafter, since 1996 a monitoring programme was planned to measure the displacement of the concrete blocks and cracks using 3-dimensional gauges, and since 2000 using a geodetic survey system with remote monitoring of the dam. Vertical movements leading to strains in the range of 20 to 42 micro strain per year have been registered since 2000 and total accumulated strain of approximately 850 micro strain was measured in 2014 (Sellier et al. 2017). During an extensive site investigation conducted by the authors a concrete block located in the left flank was considered as the one with the most significant swelling, cracks and damage. See Fig. 4. The geometry and layout of the dam plus average temperature in the upstream

![](image1)

Fig. 3 Flowchart of the SU-ASR model numerical implementation.

![](image2)

Fig. 4 A perspective view of the downstream side of Kleinplaas dam in the Jonkershoek River near Stellenbosch.
Material properties and the thermal data to perform the preliminary thermal analysis and subsequent chemo-mechanical analysis are shown in Table 1. Note that permission to extract core samples from the actual dam was not obtained. The material model parameters in Table 1 are based on the specified compressive strength for the concrete used in the dam, and knowledge of the local aggregate type reportedly used in the concrete (Alaud and van Zijl 2017).

Figure 6 illustrates the temperature history that is used in the transient heat-diffusion analysis of the dam. Due to the difficulties to access the temperature data measured at the dam station, this data was collected from a climate station installed at Stellenbosch University, 8.2 km away from the dam structure (Meijers 2018). This seasonal temperature is used only for the downstream and top surface of the dam since it is in the direct contact with the sunlight. For the upstream surface of the dam scaled values of the seasonal temperature of the water with the average of 6-10°C are used. It is worth noting that the Kleinplaas dam is a balancing dam and is kept full most of the time during a year. Hence, the spatial fluctuation of the water level during a season is not incorporated in this analysis.

### 3.2 Thermal analysis

Temperature history is a key factor driving the ASR in massive dams. Before performing an ASR and stress analysis, it is necessary to determine the temperature field in space and time. By assuming an initial condition for temperature \( \theta_i \) at time \( t_i \) at each integration point in the dam, the FEA code is used to do a transient thermal analysis. Subsequently, the results from thermal

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**Table 1 Material properties for concrete, soil fill and rock used in the FE model of Kleinplaas dam (CEB-fib, 2013).**

|           | Young modulus \( E_m \) (GPa) | Poisson’s ratio \( \nu \) | Tensile strength \( f_t \) (MPa) | Fracture energy \( G_f \) (N/m) | Thermal conductivity \( k \) [W/(m K)] | Specific heat \( c \) [kJ/(kg K)] | Thermal expansion coefficient \( \alpha \) \( (10^{-5}) \) |
|-----------|-------------------------------|---------------------------|----------------------------------|----------------------------------|--------------------------------------|-------------------------------------|----------------------------------|
| Concrete  | 27.0                          | 0.17                      | 2.9                              | 140.0                            | 1.75                                 | 0.75                                | 1.0                              |
| Rock      | 20.0                          | 0.25                      | -                                | -                                | 0.75                                 | 0.85                                | 0.5                              |
| Soil fill | 0.15                          | 0.2                       | -                                | -                                | 0.55                                 | 1.00                                | 0.5                              |
analysis are used in the SU-ASR FE code through defining a predefined field temperature variation in space and time at each integration point of the FE model in order to compute the reaction extent and consequent ASR strains. Figs. 7a to 7d show the results of thermal analysis considering the thermal interaction between the concrete material, filled-soil and rock foundation. These figures show the thermal variation from 1982 to 2014. The effects of solar radiation in thermal analysis of the dam are ignored in this study. The initial temperature field is shown in Fig. 7a and is obtained using an average temperature for the upstream, downstream, filled-soil material and foundation boundary surface areas. Seasonal temperature variations for the upstream and downstream surfaces of the dam are incorporated in the transient thermal analysis. It is evident that the thermal gradient is higher in the downstream face of the dam mainly because of the more exposure to direct sunlight.

3.3 Calibration of the numerical model
Firstly, it is important to calibrate the model in terms of the expansion and displacement information that is measured for this dam. Unfortunately, the complete set of data is not available for this dam. Therefore, for the purpose of the current research some information about the strain rate since 2000 to 2014, which is reported in literature, is used to calibrate the model (Sellier et al. 2017). For the purpose of this analysis, the mechanical loadings are considered as the gravity load, and the hydrostatic pressure of the water upstream of the dam. Figure 8 illustrates the total strain for the crest of the concrete block modelled in this research. Calibration of
the model is a trial and error process and the code is re-run several times to estimate the ASR parameters that predict the measured strain with adequate accuracy. It is evident that the dam has experienced gradual movement towards the downstream for many years after its construction. Figure 9 shows the computed horizontal displacement of the dam. The maximum value of the displacement is about 30 mm and the value after 32 years is 15 mm. The activation of ASR at the upstream wall of the dam after about 15 years is the reason of the reverse movements in the horizontal direction of the crest. Table 2 shows the ASR parameters that are computed based on the calibration of the SU-ASR model for the Kleinplaas dam.

### 3.4 Results of the ASR analysis

In this section the results of the FE analysis of the Kleinplaas concrete gravity dam are presented and discussed. Note that mechanical loading is the self-weight, as well as the hydrostatic water pressure along the upstream face of the dam wall. For purpose of simplicity and reducing the cost of analysis, only the dam structure is modelled in the mechanical analysis and the soil fill and foundation are not modelled. Contour diagrams of the reaction extent are shown in Figs. 10a to 10c. It is observed that in the dam wall after 32 years of being exposed to ASR, the extent of the ASR was complete and can be deemed to have stopped or be drastically reduced by 2014. The report on this dam (DWS 2009) also confirms this hypothesis.

Figure 11 presents the material damage variable after 32 years of ASR action in the dam wall. It is evident that the concrete material is highly degraded. In this figure the extent of the ASR damage \( \text{d}_{\text{asr}} \) is about 24.4% after 32 years. As shown in Table 1, the initial Young’s modulus of concrete in this study is 27 GPa. By assuming the current maximum damage from ASR, approximately 6.6 GPa reduction in E-Modulus likely has occurred in the dam. Note that isotropic damage is assumed here, and no distinction is made in the reduction

| ASR parameter          | Values |\
|------------------------|--------|
| Characteristic time \( \tau_c \) (days) | 200    |\
| Latency time \( \tau_l \) (days) | 80     |\
| ASR material dilatancy \( \beta \) (%) | 0.2    |\

Table 2 Material properties for concrete, soil fill and rock used in the FE model of Kleinplaas dam (CEB-fib, 2013).
of the E-modulus in orthogonal directions in the dam wall. This material degradation can change the dynamic behaviour of the dam, reduce the mechanical strength of the material and jeopardise the safety of the dam especially during seismic events.

Figure 12 illustrates the result of the FE modelling of the dam wall affected by ASR induced expansions. The important issues in the downstream side of the dam are expansion, cracking and pop outs of the aggregates. The embankment constructed close to the downstream side of the dam could help to hamper the thermal activation mainly due to different thermal conductivity property of the soil used in this area (see Table 1). In this figure a compatible result between FE modelling and the actual crack in the downstream wall of the dam is illustrated. From the plastic principal strains shown as vectors in Fig. 12, it can be concluded that several micro cracks are present in the dam. At the downstream face, the large plastic strain vectors indicate a significant local crack, but this crack does not penetrate deep into the dam, and can be considered as a superficial crack. It is proposed that this hypothesis be further examined by taking the cores from the downstream side of the dam especially in the cracked area. The large plastic strains are located just below the intersection between the exposed dam wall and the soil fill, which leads to thermal strain gradients (Fig. 7). The gallery opening contributes to strain gradients in this region, albeit predominantly deeper into the wall. Hence, a combination of strain gradients and high ASR swelling rate is postulated to cause the high plastic strain at the shown position on the downstream face, roughly at the gallery upper height.

During the technical investigation carried out by the authors, an abnormal seepage was observed in the upstream wall of the dam inside the gallery. The extensive irreversible maximum plastic strains could possibly explain the reason for this seepage. The micro cracks and voids that developed during the service life of the dam due to the effects from mechanical and chemical processes in the left and top side of the gallery could possibly join together and create a passage through the gallery, thus water can flow from the upstream wall to the gallery.

4. Combined action of ASR and seismic excitation in Kleinplaas dam

The proposed model is used to predict the long term behaviour of the dam due to a synthetic ASR, and then the current state of the structure is used as an initial state.
4.1 Seismic analysis of Kleinplaas dam

From forced vibration tests on dams (Clough and Penzien 2003), damping ratios in the range from 2 to 5% have been determined. In dynamic analysis, dissipation mechanisms such as dashpots or inelastic material behaviour can be implemented. In this study the damping ratio used is \( \zeta_1 = 3\% \) fraction of critical damping for the first mode of vibration of the dam. From a natural frequency extraction analysis, the first mode of vibration of the dam is found to be \( \omega_1 = 85.6 \text{ rad/s} \). By assuming Rayleigh stiffness-proportional damping, \( \eta = \frac{2\zeta_1}{\omega_1} \) is computed to be \( 7.0093 \times 10^{-4} \text{ s} \). The results of the modal analysis for the different mode shapes are presented in Fig. 13. The acoustic wave velocity of water, \( C_0 \), used is \( 1438.5 \text{ m/s} \). The loading consists of self-weight of the dam, hydrostatic and hydrodynamic effects of the reservoir and the transverse components of earthquake loading.

The Kleinplaas dam is located in the Western Cape province of South Africa. In this region the peak ground acceleration (PGA) is \( 0.15 \text{ g} \) based on SANS seismic code of South Africa (SABS 2011). Unfortunately seismic signals for the region are not available, hence for the purpose of illustrating seismic effect, a scaled signal from the Koyna dam is used. Figure 14 illustrates the input seismic signal that is extracted from the Koyna dam earthquake event. Hence, the Koyna signal is scaled in order to tune the PGA to be used in this research. Finally, a scale factor of 0.35 is adopted to reduce the ground acceleration.

The hydrodynamic loading is modelled by applying assumptions of the reservoir modelling comprising compressible, inviscid, small amplitude motion, irrotational fluid with the Helmholtz equation and appropriate boundary conditions as mentioned in the previous section. The effect of Fluid-Structure Interaction (FSI) was evaluated in the recent article by the authors (Pourbehi et al. 2019). In this research, however, the dam shows a low level of horizontal displacement (less than 2 mm) during the FSI modelling strategy as it can be observed in Fig. 16. The dam is categorised as a small dam (only 20.5 m height) and therefore the stiffness of the dam is very high. Hence, the effects of the modelling strategies with an empty dam or added mass technique modelling are not important for this case. The dam is analysed in the time domain using Newton’s method as a numerical technique for solving non-symmetrical nonlinear equilibrium equations using a time step of 0.02 seconds. The numerical analyses are carried out for two cases, without ASR, and with ASR deterioration for 32 years.

\[
\begin{align*}
\text{Mode 1: } & 85.6 \text{ rad/s} \\
\text{Mode 2: } & 228.2 \text{ rad/s} \\
\text{Mode 3: } & 277.6 \text{ rad/s} \\
\text{Mode 4: } & 470.3 \text{ rad/s}
\end{align*}
\]

Fig. 13 Frequency analysis and mode extraction of Kleinplaas dam.

\[
\begin{align*}
\text{Fig. 14 Horizontal seismic acceleration histories for the Koyna dam vs. time.}
\end{align*}
\]
4.2 ASR and earthquake interaction in Kleinplaas dam

In this section the numerical simulations using the SUASR finite element analysis approach are used to assess and predict the dynamic stability of a dam structure considering fluid-structure interaction and are also used to investigate the evolution of damage associated with inception and development of macro cracks in the dam structures due to the combined effect of the ASR and seismic loading on the dam.

The seismic analysis of the Kleinplaas dam without ASR reveals that the tensile damage does not occur in the body of the dam during the dynamic analysis under the input signal in Fig. 14, scaled by factor of 0.35.

The result of the combined analysis of the ASR and seismic load for tensile damage is shown in Fig. 15. These figures illustrate that gradual development of the damage occurs in the body of the dam and around the gallery mainly due to reduction in stiffness. The dam experiences a major localised crack in the downstream parapet wall, which propagates through the interior body of the structure and changes the dynamic behaviour of the dam. The thermal gradient is at a maximum on the downstream surface of the dam wall that leads to the higher ASR strains in comparison to the upstream wall surface, where the temperature is lower due to the contact of this surface with water in the reservoir.

Furthermore, Figs. 16 and 17 show the time histories of horizontal displacement at the dam crest for modelling without ASR and combined action of ASR and seismic load, respectively. The displacement of the ASR affected dam is larger than the case when ASR is not considered. This is due to the decrease in the material stiffness of the concrete and inelastic behaviour and damage in the dam with crack opening. The maximum crest displacement for the combined action of ASR and seismic load is 38.4 mm, which is significantly larger than the crest displacement when only ASR effect is considered and is equal to 15 mm (see Fig. 9). It is worth noting that due to the combined action of seismic load and ASR an irreversible horizontal displacement of 23.4 mm is added to the dam horizontal displacement when only ASR effect is considered.

5. Conclusion

This article presented the nonlinear response of an ASR affected concrete gravity dam (the Kleinplaas dam) after
long term operation followed by a subsequent seismic event using the code developed in this research. In the chemo-thermo-mechanical model, ASR kinetics is combined with a damage plasticity model using a finite element approach that incorporates the ASR expansion effects by temperature, humidity, confinement under 3D stress states and non-uniform time dependent material degradation. The model is applied to the Kleinplaas dam in Stellenbosch, South Africa, which has been suffering from ASR from 1983, to predict the long term behaviour of the dam wall due to the ASR. Subsequently, a seismic analysis is performed, considering the state of the structure at the end of the ASR analysis as an initial state for the analysis. The following conclusions are drawn:

1. In the rather small concrete dam, the computed result is that full ASR extent has been reached after the 32 year period throughout most of the dam section. The exception is a part of the upstream wall in contact with the water, where colder conditions delay the reaction.

2. The computed response to the ASR process over the 32 year period of existence of the Kleinplaas dam shows agreement with cracks observed in the downstream face and gallery on inspection. However, the model does not capture actual localised crack growth under ASR action only. High computed plastic strains are found on the downstream face, in the vicinity of observed cracking and leakage.

3. The results show that over 24% of the ASR induced damage, in terms of reduction in elastic modulus, has occurred in the dam cross section during the years from 1982 to 2014.

4. A seismic event of the magnitude of 0.15 g maximum acceleration expected in the region, does not lead to permanent horizontal displacement of the crest, in absence of ASR-induced damage in the dam. However, if this seismic event occurs after development of ASR damage as computed here for the 32 year period, a localised crack arises from the downstream face and grows inward. Two more cracks arise in the gallery roof and floor. Due to these localised cracks, significant permanent horizontal displacement of the dam crest occurs.

While a 10 second seismic horizontal acceleration signal as adopted here does not lead to full instability or collapse of the dam wall, the computed response raises concern. Deeper investigation is justified into the effects of different seismic signals of both horizontal and vertical accelerations from the region, and possibly of longer duration. Strategies for repair and retrofitting of the dam in its current state can be developed and the subsequent dam response investigated with the presented model, in order to improve the dam stability performance during a possible seismic event in the future. Creep, relaxation and shrinkage are not considered here, and future research and modelling should be conducted to include these phenomena. Whilst computational procedures exist to incorporate these time-dependent phenomena, appropriate model parameter characterisation remains a challenge given the available measured data for particular dam structures.

References
Alaud, S. and van Zijl, G. P. A. G., (2017). “Combined action of mechanical pre-cracks and ASR strain in concrete.” *Journal of Advanced Concrete Technology*, 15(4), 151-164.

Bazant, Z. P. and Steffens, A., (2000). “Mathematical model for kinetics of alkali-silica reaction in concrete.” *Cement and Concrete Research*, 30(3), 419-428.

Capra, B. and Bournazel, J. P., (1998). “Modeling of induced mechanical effects of alkali-aggregate reactions.” *Cement and Concrete Research*, 28(2), 251-260.

Capra, B. and Sellier, A., (2003). “Orthotropic modelling of alkali-aggregate reaction in concrete structures: numerical simulations.” *Mechanics of Materials*, 35(8), 817-830.

CEB-fib, (2013). “fib model code for concrete structures 2010.” Lausanne, Switzerland: fédération internationale du béton (fib).
Charlwood, R. G., (2009). “Predicting the long term behavior and service life of concrete dams.” In: E. Bauer, S. Semprich and G. Zenz, Eds. Proceedings of the 2nd International Conference on Long Term Behavior of Dams, Graz, Austria 12-13 October 2009. Graz: Verlag der Technischen Universität Graz.

Clough, R. W. and Penzien, J., (2003). “Dynamics of structures.” 3rd Ed. Berkeley, CA, USA: CSI Computers and Structures, Inc.

Comby-Peyrot, I., Bernard, F., Bouchard, P. O., Bay, F. and Garcia-Diaz, E., (2009). “Development and validation of a 3D computational tool to describe concrete behaviour at mesoscale: application to the alkali-silica-reaction.” Computational Materials Science, 46(4), 1163-1177.

Dunant, C. F. and Scrivener, K. L., (2010). “Micro-mechanical modelling of alkali-silica-reaction-induced degradation using the AMIE framework.” Cement and Concrete Research, 40(4), 517-525.

Dyer, T., (2014). “Concrete durability.” London: CRC Press.

Giorla, A. B., Scrivener, K. L. and Dunant, C. F., (2015). “Influence of visco-elasticity on the stress development induced by alkali-silica-reaction.” Cement and Concrete Research, 70, 1-8.

ISE, (1992). “Structural effects of alkali-silica reaction.” London: The Institution of Structural Engineers.

DWS, (2009). “Kleinplaas dam, third dam safety inspection report.” Pretoria, South Africa: Department of Water and Sanitation of South Africa.

Larive, C., (1998). “Apports combinés de l’experimentation et de la modélisation à la comprehension del’alcali-réaction et de ses effets mécaniques.” Thesis (PhD). Ecole Nationale des Ponts et Chaussées, Paris. (In French)

Lee, J. and Fenves, G. L., (1998). “Plastic-damage model for cyclic loading of concrete structures.” Journal of Engineering Mechanics, 124(8), 892-900.

Lemarchand, E., Dormieux, L. and Ulm, F.-J., (2002). “Elements of micromechanics of ASR-induced swelling in concrete structures.” Concrete Science and Engineering, 4, 12-22.

Li, K. and Coussy, O., (2004). “Numerical assessment and prediction method for the chemico-mechanical deterioration of ASR-affected concrete structures.” Canadian Journal of Civil Engineering, 31(3), 432-439.

Liaudat, J., Carol, I., López, C. M. and Saouma, V. E., (2018). “ASR expansions in concrete under triaxial confinement.” Cement and Concrete Composites, 86, 160-170.

Meijers, J. P., (2018). “Stellenbosch weather: temperature graphs [online].” Stellenbosch University. Available from <http://weather.sun.ac.za/graphs/temperature> [Accessed 25 July 2019].

Morenon, P., Multon, S., Sellier, A., Grimal, E., Hamon, F. and Bourdarot, E., (2017). “Impact of stresses and restraints on ASR expansion.” Construction and Building Materials, 140, 58-74.

Multon, S., Sellier, A. and Cyr, M., (2009). “Chemo-mechanical modeling for prediction of alkali silica reaction (ASR) expansion.” Cement and Concrete Research, 39(6), 490-500.

Multon, S. and Toulemonde, F., (2006). “Effect of applied stresses on alkali-silica-reaction-induced expansions.” Cement and Concrete Research, 36(5), 912-920.

Nayak, P. and Maity, D., (2013). “Seismic damage analysis of aged concrete gravity dams.” International Journal for Computational Methods in Engineering Science and Mechanics, 14(5), 424-439.

Pourbehi, M. S., (2018). “Numerical modelling of alkali silica reaction in concrete dams.” Thesis (PhD). Stellenbosch University, Stellenbosch, South Africa.

Pourbehi, M. S., van Zijl, G. P. A. G. and Strasheim, J. A. vB., (2019). “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.

SABS, (2011). “Seismic code SANS 10160-4: basis of structural design and actions for buildings and industrial structures, part 4: seismic actions and general requirements for building.” Pretoria: South African Bureau of Standards.

Saouma, V. E. and Perotti, L., (2006). “Constitutive model for alkali-aggregate reactions.” ACI Materials Journal, 103(3), 194-202.

Sellier, A., Grimal, E., Multon, S. and Bourdarot, E., (2017). “Swelling concrete in dams and hydraulic structures: DSC 2017.” London: ISTE Ltd.

Simulia, (2016). “Abaqus 2016 theory guide.” Providence, Rhode Island, USA: Dassault Systèmes Simulia Corp.

Steffens, A., Li, K. and Coussy, O., (2003). “Aging approach to water effect on alkali-silica reaction degradation of structures.” Journal of Engineering Mechanics, 129(1), 50-59.

Ulm, F., Coussy, O., Li, K. and Larive, C., (2000). “Thermo-chemo-mechanics of ASR expansion in concrete structures.” Journal of Engineering Mechanics, 126(3), 233-242.

Valiappan, S. and Chee, C., (2009). “Aging degradation of concrete dams based on damage mechanics concepts.” In: Y. Yuan, J.Cui, and H. A. Mang, Eds. Computational structural engineering. Heidelberg: Springer Netherlands, 21-35.

Zienkiewicz, O. C., (2006). “The finite element method for solid and structural mechanics.” 6th ed. Amsterdam: Elsevier B.V.