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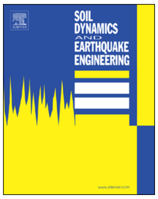

Integrative seismic safety evaluation of a high concrete arch dam

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ABSTRACT

An integrative seismic safety evaluation of an arch dam should include all sources of nonlinearities, dynamic interactions between different components and the external loads. The present paper investigates the calibration procedure and nonlinear seismic response of an existing high arch dam. The first part explains the conducted analyses for the static and thermal calibrations of the dam based on site measurements. The second part investigates the nonlinear seismic analysis of the calibrated model considering the effect of joints, cracking of mass concrete, reservoir–dam–rock interaction, hydrodynamic pressure inside the opened joints and the geometric nonlinearity. Penetration of the water inside the opened joints accelerates the damage process. The integrative seismic assessment of a case study shows that the dam will fail under the maximum credible earthquake scenario. The dam is judged to be severely damaged with extensive cracking and the joints undergo opening/sliding. A systematic procedure is proposed for seismic and post-seismic safety of dams.

1. Introduction

Arch dams are complex structures in which their performance can be affected by both internal and external parameters. Integrative seismic analysis of an arch dam requires appropriate information on material properties, their elastic and damage behavior and the external factors that may affect the response. A reliable numerical model for nonlinear analysis and safety assessment of an arch dam is necessary. The developed model should be calibrated based on the existing condition of the dam. Usually calibration is utilized on static and thermal properties of the material and the dynamic properties are obtained either by laboratory tests or using the universal guidelines in similar cases. Results of the numerical models are compared with those recorded during operational period of the dam to determine the material constants. Fig. 1 shows the general methodology which can be used to realize the real-file behavior of the concrete dams.

In the present paper, different parameters affecting the nonlinear responses of concrete arch dams and their mathematical representations are explained. The main contribution in this paper is coalescing various advanced methodologies into a single realistic analysis. In addition, some of the parameters which are usually neglected in analysis and assessment of arch dams are considered in this paper, e.g., mass foundation with infinite elements, water pressure inside the opened joints, large deformation of free cantilevers under severe ground motions, and solar radiation effects on non-uniform temperature distribution. An existing arch dam is selected as case study and the step-by-step procedure for static and thermal calibration of the numerical model is discussed. Finally, using the appropriate properties of the material and also utilizing the advanced interaction relation between dam–reservoir–foundation, the vibrational characteristics of the coupled system is realized. Hazard analysis of the dam site is implemented and a set of appropriate ground motions are selected based on the maximum credible level (MCL) scenario. The main objective of this study is to calibrate the thermal and structural response based on the finite element model. The nonlinear seismic and post-earthquake failure analysis of the dam considering the major sources of nonlinearities and interactions are evaluated and discussed. The results are extracted in terms of displacements, stresses, joint opening, and crack profiles.

2. Literature review

Modeling the joints (contraction, peripheral and lift joints) have the important role on both the static and the seismic analysis of concrete arch dams. Ahmadi et al. [1] introduced a nonlinear joint element with coupled tension–shear behavior for analysis of arch dam–reservoir system. Azmi and Paultre [2] proposed a special joint model which was able to model the contact between two adjacent nodes in three-dimensional (3D) domain. Du and Tu [3] combined explicit finite element method with transmitting boundary to study the effects of contraction joint opening on the

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Nomenclature

$a_n(t)$	normal acceleration on the fluid–structure interface
$a_n^{struc}(x, y, z, t)$	normal acceleration on the upstream face of dam
$\overline{a}$	solar absorptivity of surface
A_{eff}	effective area for each node within an element
C_{cnt}	cohesion factor in contact element
C	specific heat of concrete
C_0	velocity of pressure wave in water
C_s	Stefan–Boltzman constant
e	the ratio of the position vectors (concrete failure surface)
e^*	emissivity of surface
E_c	elasticity modulus of concrete
E_{c_o}	linear elasticity modulus of concrete
E_F^{Sat}	deformation modulus of foundation (saturated region)
E_F^{Dry}	deformation modulus of foundation (dry region)
f_c	compressive strength of concrete
f_{cb}	bi-axial compressive strength of concrete
f_t'	tensile strength of concrete
F_n, F_r, F_s	components of the force vector in contact element
F_g	sliding force in contact element
F_t	resultant shear force in contact element
$F_{eff}(\widehat{t}, h_{jt}, r_{jt})$	effective nodal force on the inner nodes of dam perpendicular to radial direction
h_{jt}	distance from water free surface in the directional of gravitational force
h_c^*	convection coefficient
H_0	total reservoir depth
I_1, I_2, I_3	stress invariants
I_t	total amount of solar energy reaching the surface
J_1, J_2, J_3	deviatoric stress invariants
$\overline{\mathrm{JOD}}_r(\widehat{t}, h_{jt}, r_{jt})$	joint opening displacement in radial direction
k_{ij}	Cartesian component of the conductivity tensor
K_n	normal stiffness of contact element
K_t	tangential stiffness of contact element
M_i	growth shape function in infinite elements
n_i	Cartesian component of normal boundary vector on the dam–reservoir interface
n_i^{air}	Cartesian component of normal boundary vector on Γ_{air}
N_i	standard shape function in infinite elements
$P(x, y, z, t)$	hydrodynamic pressure at the specific location and time
$P_{tot}(\widehat{t}, h_{jt}, r_{jt})$	total pressure at the joint location
$P_{st}(h_{jt})$	hydrostatic pressure at the specific level
$P_{dyn}^{net}(\widehat{t}, h_{jt})$	net hydrodynamic pressure at the specific level and time
q_a	applied (solar radiation) flux
q_c	convective flux
q_r	radiative flux
$\widehat{Q}$	internal heat generation per unit volume
r_1, r_2	position vectors of meridians in $\theta=0$ and $\theta=60^\circ$ (concrete failure surface)
r_{jt}	distance in radial direction measured from upstream face of dam
t	time
t_0	time in which T_{air} is maximum
$\bar{t}$	time at which $T_{air}=T_{mean}$
$\widehat{t}$	time with respect to dynamic loading
T	temperature of medium
T_0	grouting temperature of dam
T_b	mean annual water temperature at the bottom
T_s	mean annual water temperature at the surface
T_{canst}	constant temperature of the foundation (T_{rock})
T_{max}	maximum of mean monthly air temperature
T_{min}	minimum of mean monthly air temperature
T_{mean}	mean annual air temperature
$T_{res}(y, t)$	reservoir temperature in a depth of y and the time t
$T_{air}(t)$	air temperature
V_n, V_r, V_s	components of the displacement vector in contact element
α_0	wave reflection coefficient at the reservoir bottom and sides
α_{cnt}	angle between the two components of the in-plane shear forces in contact element
α_M	mass proportional Rayleigh damping coefficient
α_V	thermal expansion coefficient of concrete
$\beta_{12}, \beta_{23}, \beta_{13}$	shear transfer factors corresponding to the principal directions (concrete constitutive model)
β_K	stiffness proportional Rayleigh damping coefficient
η_1, η_2, η_3	ratio of the softened to the isotropic Young's modulus in principal directions (concrete constitutive model)
μ_{cnt}	friction coefficient in contact element
θ	lode angle (concrete failure surface)
ρ_c	mass density of concrete
ρ_F^{Sat}	mass density of foundation rock (saturated region)
ρ_F^{Dry}	mass density of foundation rock (dry region)
ρ_w	mass density of water
$\sigma_1, \sigma_2, \sigma_3$	principle stress components (where $\sigma_1 > \sigma_2 > \sigma_3$)
τ_o	phase differences between maximum T_{air} and maximum T_{res}
υ_c	Poisson's ratio of concrete
υ_F	Poisson's ratio of foundation rock
η, ξ, ζ	local coordinate system for infinite element assuming ξ as infinite direction
$\overline{\xi}$	effective damping ratio
ψ	angle between the normal on dam face and the horizontal plane
Γ_{air}	air–dam interface
Γ_{res}	reservoir–dam wet interface
$\Upsilon(\theta)$	elliptic trace (concrete failure surface)
$[B_n]$	small strain–displacement relationship in the rotated element coordinate system
$[B_v]$	small strain–displacement relationship in the original element coordinate system
$[B^{inf}]$	strain–displacement relationship in the infinite element
$[C^F]$	equivalent damping matrix for fluid part
$[C^S]$	damping matrix for structural part
$[D]_{els}^{lc}$	local elastic stiffness tensor (concrete constitutive model)
$[D]_{crk}^{lc}$	local cracked stiffness tensor (concrete constitutive model)
$[D]_{els}^{t}$ and $[D]_{els}^{r}$	main components of the local elastic stiffness tensor (concrete constitutive model)
$[D]_{crk}^{t}$ and $[D]_{crk}^{r}$	main components of the local cracked stiffness tensor (concrete constitutive model)
$\{f^S\}$	vector of body force and hydrostatic force
$\{f^F\}$	the component of the force due to acceleration at the reservoir boundaries
$\{F_e^{nr}\}$	element restoring force vector
$[G^F]$	equivalent mass matrix for fluid part
$[\bar{J}]$	Jacobian matrix for the infinite elements
$[K_e]$	element tangent stiffness matrix
$[K^F]$	equivalent stiffness matrix for fluid part
$[K^S]$	stiffness matrix for structural part