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A methodology for the assessment of the effect of climate change on the thermal-strain–stress behaviour of structures

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ABSTRACT

Thermal loads can cause significant stresses in some structures such as bridges or arch dams. Studies in arch dams show that thermal loads have the most significant effect for causing cracking than other service loads. Moreover, since researches on climate change announce that mean temperature on Earth is expected to increase, the assessment of the impact of the future temperature increase on the structural behaviour of sensitive infrastructures should be considered. This paper proposes a methodology for the assessment of the impacts of global warming on the structural behaviour of infrastructures. The paper links future climate scenarios to the thermal, stress and displacement fields of the structure. The methodology is illustrated with a case study: La Baells arch-dam. The expected stress and displacement fields of the dam under several future climatic scenarios were computed by finite element models. Concrete temperature are expected to increase up to 5.6 K, which will make annual average radial displacements increase in some cases even more than 100%. Tensile stresses are also projected to change and should be adequately monitored in the future. Finally, several adaptation strategies are outlined.

1. Introduction

Structures are subjected to environmental actions affecting their performance and safety. Among these actions, thermal loads are of special interest in some civil infrastructures, such as arch dams or bridges where stresses may be induced by thermal action due to its hyperstatic nature. Thermal loads cause the second most major repairs in dams under service [1] and they are crucial in the monitoring task of these structures [2–4]. Moreover, thermal loads have the most significant effects for causing downstream face cracks in arch dams in comparison with other service loads [5,6].

According to the Intergovernmental Panel on Climate Change (IPCC), mean temperature increased 0.76 K from 1850–1899 to 2001–2005 [7]. Studies have estimated an average global rise in temperature from 1.4 to 5.8 K between 1990 and 2100 and heat waves will be more intense, more frequent and longer [8]. Future climate predictions in the Earth are estimated by global climate models (GCM), which are numerical representations of the climate system. The concentration of substances that are potentially radiatively active (e.g., greenhouse gases, aerosols) in the atmosphere are used as inputs to the models. Future projections of emissions of these substances are denoted as emissions scenario and are based on a set of assumptions about driving forces (such as technological change, demographic and socioeconomic development) and their relationship [9]. The IPCC defined four scenario families (A1, A2, B1 and B2), which cover a wide range of future characteristics, such as demographic evolution, economic development or technological change. A1 family is divided into three groups which are distinguished by the technological emphasis: fossil-intensive (A1F1), non-fossil energy source (A1T) and a balance across all sources (A1B) [9]. These scenarios families have been used to project future atmospheric green house gas (GHG) concentrations.

Recently, the IPCC has just published a new generation of scenarios denoted as Representative Concentration Pathways (RCP) [10]. RCP are prescribed pathways for greenhouse gas and aerosol concentrations, together with land use change. Four RCP have been defined: RCP2.6, RCP4.5, RCP6 and RCP8.5, where the numbers refer to radiative forcings.

GCM have a typical resolution of hundreds of kilometres in the horizontal directions and their predictions are suitable at a global scale. Prediction at a regional or local scale have been carried out with dynamic or empirical downscaling methodologies. One of the most recent predictions at a regional scale for Europe and the North of Africa were developed in the EMSEMBLES project [11]. Predictions were computed with a downscaling methodology using regional climate models (RCM) driven by GCM with several

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Nomenclature

Abbreviations

AAEM	age-adjusted effective modulus
CDF	cumulative distribution function
FEM	finite element method
GCM	global climate model
GHG	green house gas
IPCC	Intergovernmental Panel on Climate Change
RGM	regional climate model
RCP	Representative Concentration Pathways
RMSE	root mean squared error
A	anisotropy index
A_c	area of the cross section
$A_{w,s}$	annual water temperature amplitude at the surface of the reservoir
a	solar absorptivity
b	coefficient
$\mathbf{C}$	specific heat matrix
C_s	Stefan–Boltzmann constant
c	specific heat
c_s	specific heat capacity of air
$\mathbf{D}$	vector of nodal displacements
E_s	moisture emissivity coefficient
e	emissivity
e_s	saturation vapour pressure
E_c	modulus of elasticity of concrete
$E_{c,\mathrm{ef}}$	effective modulus of elasticity of concrete
$E_{c,\mathrm{adj}}$	aged-adjusted effective modulus of elasticity of concrete
$\mathbf{F}$	vector of applied forces
f_{cm}	mean compressive strength of concrete
$G_{c,\mathrm{adj}}$	aged-adjusted effective shear modulus of concrete
g_r	ground reflectivity
$\mathbf{H}$	vector of applied heat flows
H_d	height of the dam
H_{dr}	depth of the reservoir
H_G	daily global insolation on a horizontal surface
$H_{G,o}$	extraterrestrial daily global insolation on a horizontal surface
H_r	relative humidity
h	convection coefficient
h_w	latent heat of evaporative water
I_G	hourly global insolation on a horizontal surface
$I_{G,o}$	extraterrestrial hourly global insolation on a horizontal surface
$I_{T,G}$	hourly global insolation on a tilted surface
I_b	hourly beam insolation on a horizontal surface
I_d	hourly diffuse insolation on a horizontal surface
J	creep compliance function
$K_{c,\mathrm{adj}}$	aged-adjusted effective bulk modulus of concrete
$\mathbf{K_S}$	stiffness matrix
$\mathbf{K_T}$	thermal conductivity matrix
K_t	daily global clearness index
k_t	hourly global clearness index
k_d	hourly diffuse fraction
n_s	notional size
P	total air pressure
q	heat flux
q_c	heat flux due to convection
q_{ev}	heat flux due to water evaporation
q_m	moisture evaporative flux
q_s	heat flux due to solar radiation
q_r	heat flux due to long wave radiation exchange
R_b	ratio of the hourly beam insolation on a titled surface to that on a horizontal surface
R	relaxation function
r_o	ratio of extraterrestrial hourly global insolation to extraterrestrial daily global insolation
r_t	ratio of hourly global insolation to daily global insolation
$s_{\zeta,j}$	mean monthly standard deviation of variable ζ at month j
t	time
z	vertical distance between the dam crest and the water surface of the reservoir
α_o	extraterrestrial daily-average solar elevation angle
β	slope of surface
$\beta_{\zeta,j}$	monthly ratio or difference between $\overline{\zeta_j}$ from different periods
ΔA_r	amplitude increment due to solar radiation
$\Delta\theta_r$	temperature increment due to solar radiation
ε	strain
$\varepsilon_{c\sigma}$	stress dependent strain
$\varepsilon_{c\sigma,\mathrm{ce}}$	creep component of stress dependent strain
$\varepsilon_{c\sigma,\mathrm{es}}$	elastic component of stress dependent strain
$\gamma_{\zeta,j}$	monthly error variability of the variable ζ at month j
δ	solar declination angle
$\varepsilon_{\zeta,ijk}$	normalized value of variable ζ at day i, month j and year k
ζ	climatic variable
ζ_{ijk}	value of the variable ζ at day i, month j and year k
$\overline{\zeta_j}$	mean monthly value of the variable ζ at month j
$\boldsymbol{\theta}_t$	vector of nodal temperatures at time t
θ	concrete temperature
θ_a	air temperature
$\theta_{a,i}$	mean monthly air temperature at month i
$\theta_{a,y}$	mean annual air temperature
θ_{dp}	dew point temperature
θ_{sk}	sky temperature
θ_w	water temperature
$\overline{\theta_{w,b}}$	mean annual water temperature at the bottom of the reservoir
$\overline{\theta_{w,s}}$	mean annual water temperature at the surface of the reservoir
λ	thermal conductivity
ρ	density
σ_c	concrete stress
φ	creep coefficient
ϕ	latitude
ω	solar hour angle
ω_o	sunrise hour angle

IPCC emission scenarios. Climate predictions by a given GCM or RGM and an emissions scenario are denoted as climatic scenarios.

Climate change could affect several systems and sectors such as water resources and management, food, forest products, coastal systems and low-lying areas, industry, settlement, society or human health [12]. Changes in temperature may also have significant impacts on the stress field of the structures which can rise structural and non-structural damage, such as cracking or an increase of its displacements. Consequently, the effect of the future temperature increase should be considered during the design phase of new structures and the adoption of adaptation strategies in existing infrastructures.

The integrity of built infrastructures will be affected in terms of direct structural damage and indirect losses of functionality [13]. The increase in temperatures and longer periods of drought may result in a subsidence of buildings [14] and additional loadings