Journal of Hydrology 550 (2017) 669–684

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Influence of initial reservoir level and gate failure in dam safety analysis. Stochastic approach

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ARTICLE INFO

Article history:
Received 28 October 2016
Received in revised form 15 May 2017
Accepted 16 May 2017
Available online 20 May 2017

Keywords:
Hydrology
Initial reservoir level
Spillway gate reliability
Stochastic modeling
Dam safety
Monte Carlo framework

ABSTRACT

This study proposes a stochastic methodology to assess the influence of considering variable reservoir levels prior to the arrival of floods in hydrological dam safety; introducing probability associated to gate failure scenarios. The methodology was applied to the Riaño dam (northern Spain) by analyzing the effects of incoming floods with return periods ranging from one to 10,000 years. We studied four scenarios with different gate failure rates and compared the results assuming initial reservoir level equal to the maximum level allowed in the reservoir under normal operation conditions with those considering variable initial reservoir levels. The ratio of the return periods associated to different reference levels reached in the reservoir considering variable over constant initial level ranged from 2.0 to 4.1. The ratio of the return periods obtained assuming gate failure and no failure for the same reference reservoir level ranged up to 93, 160 and 240 depending on the gate failure rate assigned. The ratio of the return periods associated to different maximum spillway discharges considering variable over constant initial reservoir level ranged from 2.5 to 6.1. However, the ratio of the return periods obtained assuming gate failure and no failure for the same discharge ranged from 0.7 to 1.1, showing no influence of gate failure. For the study case, our analysis highlighted the importance of considering the fluctuation of the initial reservoir levels and different gate failure scenarios, emphasizing that the return periods of maximum levels reached in the reservoir and maximum outflows are the variables that best represent dam and downstream hydrological safety.

1. Introduction

Overtopping due to hydrologic causes is a common mode of failure in the history of dams (ICOLD, 1995). In the standard engineering approach, hydrological assessment of dam safety for a given return period is analyzed with deterministic methods. A design flood hydrograph is obtained and routed through the reservoir-dam system assuming constant reservoir level prior to the arrival of the flood and equal to the maximum normal operating level (MNL). However, many of the involved variables have a stochastic nature (Carvajal et al., 2009; Sordo-Ward et al., 2013). In recent decades, many authors proposed probabilistic approaches accounting for the randomness associated with different variables (e.g.: Eagleson, 1972; Arnaud and Lavabre, 2002; De Michele and Salvadori, 2002; De Michele et al., 2005; Carvajal et al., 2009; Sordo-Ward et al., 2012, 2013; Paquet et al., 2013; Bianucci et al., 2013, 2015; Brigode et al., 2014; Flores-Montoya et al., 2015, 2016). Several authors had been able to obtain accurate maximum peak-inflow frequency curves within a Monte Carlo framework (Loukas, 2002; Rahman et al., 2002; Arnaud and Lavabre, 2002; Aronica and Candela, 2007). However, it is a matter of importance to characterize not only the extremal incoming reservoir floods but the hydraulic behaviour and response of dams, as their failure could have catastrophic socio-economic consequences (Serrano-Lombillo et al., 2010, 2016). In hydrological dam safety assessment, the maximum water level reached in the reservoir is the variable that best represents the hydrological safety of the dam (Bianucci et al., 2013; Serrano-Lombillo et al., 2012a; Aranda Domingo, 2014; Micovic et al., 2016). This way, the hydrological dam safety analysis does not only depend on the hydrological forcing, but also on the dam and reservoir characteristics and operation rules. Gate functionality scenarios should also be taken into account (Lewin et al., 2003; Patev and Putcha, 2005; Escuder-Bueno et al., 2012; SPANCOLD, 2012; Micovic et al., 2016) because gated-spillway dams represent about 30% of the large dams around the world (ICOLD, 2003). Gates may not open when needed because of human, mechanical, or electrical failures, among others (Lewin

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http://dx.doi.org/10.1016/j.jhydrol.2017.05.032
0022-1694/

et al., 2003; Patev and Putcha, 2005; SPANCOLD, 2012). Observed data regarding gate functionality is sparse. Several authors have estimated failure values mainly based in expert judgment. Lewin et al. (2003) estimated that the value of failure on demand associated to a single gate was 10%, while the multiple failure rate of gates due to common causes was assumed as 1% per demand. Micovic et al. (2016) assumed lower rates of failure (e.g.: 1% for single gate failure on demand), but pointed that this assumption could not be safe. Escuder-Bueno et al. (2012) estimated that the rate of failure associated to the operation of a single gate was 5% per demand if the gate was of recent construction and well-maintained. This rate increased to 15% per single gate on demand for gates with minor operation issues.

As reservoir levels fluctuate (when a flood arrives the reservoir may be partially full) the assumption of considering maximum initial reservoir level could be conservative in hydrological safety analysis (Carvajal et al., 2009). Although many authors considered initial reservoir level (Z_0) as constant (e.g.: Hsu et al., 2011; Serrano-Lombillo et al., 2012b; Sordo-Ward et al., 2012, 2013; Bianucci et al., 2013), some considered its variability (e.g.: De Michele et al., 2005; Kwon and Moon, 2006; Carvajal et al., 2009; Salvadori et al., 2011; Aranda Domingo, 2014; Micovic et al., 2016). However, most of studies are not focused on dams with gated-controlled spillway and do not consider the malfunction of gates (but see for example Kuo et al. (2008) and Micovic et al. (2016)). De Michele et al. (2005), Carvajal et al. (2009) and Aranda Domingo (2014) analyzed hydrological safety of dams, accounting for the initial reservoir level through an empirical distribution of observed fluctuation levels in the dam. They associated to each inflow hydrograph a random Z_0 in the reservoir based on the aforementioned distribution. Kwon and Moon (2006) assessed Z_0 by using data corresponding to the rainy season and concluded that Z_0 was the most sensitive variable for the estimation of dam overtopping probability. Carvajal et al. (2009) and Aranda Domingo (2014) compared the results obtained by considering Z_0 as a random variable (obtained from the statistical analysis of observed reservoir levels) to those obtained supposing Z_0 equal to MNL. They concluded that including the stochastic nature of Z_0 in hydrological studies could be interesting in irrigation dams, as their levels could significantly fluctuate during the year.

The aim of this paper is to study how initial reservoir level and gate failure can affect hydrological safety in gated-spillway dams and in the downstream river. Specific objectives are highlighted: a) to analyze the difference between the common practice in hydrological dam safety design and a more realistic approach jointly accounting for variable initial reservoir level and gate failure, b) to assess the importance of considering the effect of these variables not only on the safety of the dam but also on the safety of the downstream river, and c) to perform a sensitivity analysis of the influence of uncertain gate failure rates on the results. In the first part of the paper, we propose a methodology in order to pursue these objectives. Afterwards, we present the Riaño case study and the results we obtained, discussing and comparing them to other studies. Finally, the main findings and conclusions are highlighted.

2. Notation used

a,b: dimensionless parameters of Eq. (3). selected from the CEDEX (MARM, 2011; Jimenez-Alvarez et al., 2012) national study.
A: area of the basin (mi^2 in Eq. (2), km^2 in Eq. (3)).
ARMA: autoregressive moving average.
CEDEX: The Public Works Studies and Experimentation Centre of Spain, Ministry of Development.
$C_{g1\text{-}g2\%}$: Scenarios represented by the independent rate of failure of each gate (g1 and g2).
CN: Curve Number.
COD: Crest of dam (m.a.s.l).
d_j: duration of the maximum annual observed flood events (days).
GEV: Generalized Extreme Value distribution.
GSC: Gated spillway crest (m.a.s.l).
ICOLD: International Commission on Large Dams.
IPF: instantaneous peak-inflow (m^3/s).
K: number of gates.
M: number of years of the observed daily inflows time series.
MDF: maximum annual mean daily inflow (m^3/s).
MNL: Maximum Normal Level (maximum reservoir level to which water might rise under normal operation (ICOLD, 1994)) (m.a.s.l).
MO: Maximum outflow (m^3/s).
MWL: Maximum Water Level (maximum reservoir level which the dam has been designed to stand (ICOLD, 1994)) (m.a.s.l).
MWRL: Maximum water reservoir level (m.a.s.l).
N: number of events considered.
NSE: Nash Sutcliffe Efficiency Coefficient (Nash and Sutcliffe, 1970).
PFFC: peak-inflows frequency curve.
P_t: total maximum rainfall depth (mm).
Q_{MAX}: maximum mean daily peak-inflows (m^3/s).
Q_{min}: minimum inflow between the two flood peaks compared (m^3/s).
$Q_{o:}$ start of the receding limb (m^3/s).
Q_t: recession flow at any time (t) after the beginning of the receding limb (m^3/s).
R^2: Coefficient of determination.
SCS: Soil Conservation Service.
SPANCOLD: Spanish National Committee on Large Dams.
Tr: Return period (years).
$Tr_{MNL.}$: Return period of maximum water reservoir levels or maximum outflows obtained assuming constant initial reservoir level equal to MNL (years).
$Tr_{VAR.}$: Return period of maximum water reservoir levels or maximum outflows obtained assuming variable initial reservoir level (years).
V: maximum annual volume (hm^3).
VEM: Volumetric Evaluation Method (Girón, 1988).
VFC: Volume frequency curve.
Z_0: initial reservoir level (m.a.s.l).
α, u, γ: Parameters of the GEV distribution (scale (m^3/s for Q_{MAX} and hm^3 for V), location (m^3/s for Q_{MAX} and hm^3 for V) and shape (dimensionless) respectively).
β: recession constant expressed as the inverse units of time (t).
θ: time difference between two flood peaks (P_1 and P_2) compared (days).

3. METHODOLOGY

We developed a stochastic methodology within a Monte Carlo framework. The process is as follows (Fig. 1):

- Stochastic initial reservoir level series generation. We estimated the probability of the levels reached in the reservoir for the maximum annual flood event.
- Synthetic reservoir inflow hydrographs generation. We generated an ensemble of hydrologic loads according to available data, considering the following observed hydrograph characteristics: duration, volume and daily peak-inflow (Sordo-Ward et al., 2012).