Soil Dynamics and Earthquake Engineering 92 (2017) 109–121

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

System identification and modal analysis of an arch dam based on earthquake response records

Jian Yang[a,*,1], Feng Jin[b], Jin-Ting Wang[b], Li-Hang Kou[c]

[a] Huaneng Clean Energy Research Institute, 102209 Beijing, China
[b] State Key Laboratory of Hydroscience and Engineering, Tsinghua University, 100084 Beijing, China
[c] China Guodian Corporation, 100034 Beijing, China

ARTICLE INFO

Keywords:
Arch dam
Seismic record
Modal properties
System identification
Finite element modal analysis

ABSTRACT

The true dynamic characteristics of dams, namely, natural frequencies, damping ratios, and mode shapes, are important to earthquake-resistant design. Thus, system identification based on in-site measurements is useful for numerical analysis and health monitoring. The well-instrumented strong motion array on an arch dam in Southwestern China recorded some seismic response data. The dynamic properties of the dam are identified from records of the top five strongest earthquake motions using power spectral density functions, transfer functions, and the ARX model. The identified modal parameters of the different seismic events are compared, and the stability of the stiffness of the dam system from 2002 to 2008 and the nonuniformity in the input ground motion are indicated. A linear finite element model of the dam and a nonlinear model that considers contraction joints are constructed and calibrated to reproduce the frequencies determined from the system identification. The modal analysis highlights potential information about the dynamic characteristics of the dam. The comparison of the results of the system identification and calibration shows that the use of the nonlinear model may be reasonable in simulating the dynamic response of the Ertan Dam.

1. Introduction

The merit of strong motion records lies in the abundant information on the recurrence and characteristics of earthquakes and structural dynamic nonlinearity. However, the strong motion records of arch dams that have experienced earthquakes are very limited. Some of the important earthquake records of arch dams in the literature are shown in Table 1. Given that existing observational databases are insufficient, the studies based on the databases of actual dams are few.

Hall [1] summarized the development of the study on the dynamic and earthquake behavior of concrete dams by reviewing the literature; the resulting summary described actual earthquake observations, the experiments performed on prototype or model dams, and the analytical investigations into the dynamic properties of dams. The author also discussed the effect of different factors on the dynamic response of dams, including damping, water depth, water compressibility, and transverse joints. Fanelli et al. [2,3] presented the dynamic behavior of the Talvacchia Arch Dam in Italy in forced vibration tests and earthquake records and investigated the influence of environmental conditions (water level and temperatures) and the structural characteristics of the dam dynamic response. The study reported the phenomenon in which resonant frequencies initially increase with rising water level and then decrease with a further rise, as well as subsequent studies [4–10]. This phenomenon is usually attributed to the comprehensive effects of the added mass from water pressure, stiffness change (opening and closing of contraction joints), and damping ratio. Loh et al. [4,5] investigated the dynamic characteristics of the Fei-Tsui Dam during seismic events and ambient vibration tests using an autoregressive exogenous (ARX) model. The results showed that the damping ratio of the Fei-Tsui dam from the strong motion input (about 9–14%) was greater than the results of ambient tests (2–3%). The author also pointed out that the damping ratio of the Fei-Tsui dam increases with the increasing natural frequency of the system. Darbre [11] presented the basic principles of strong motion instrumentation schemes for dams and emphasized the recording of the free field motions at dam sites, the effective motions at abutments, and global dam responses. Then, he estimated and compared the dynamic properties of five Swiss dams (Grande Dixence, Mauvoisin, Punt dal Gall, Emosson, and Mattmark) during earthquakes with power spectral density (PSD) functions and transfer functions (TF) [12]. The results implied that the simple identification techniques are not well suited to a comprehensive identification of the dynamic characteristics of dams. Proulx

* Corresponding author.
E-mail address: yangjian@hnceri.com (J. Yang).
[1] The main part of this work was performed as a doctoral student in Tsinghua University by the corresponding author.

http://dx.doi.org/10.1016/j.soildyn.2016.09.039
Received 18 August 2015; Received in revised form 5 September 2016; Accepted 25 September 2016

Table 1
Selected strong motion records of arch dams in the world.

Name	Region	Completion	Height/m	Earthquake	Epicentral distance/km	Magnitude	Peak acceleration[a]	Water level[b] /m	Remarks
Longyangxia [18]	China	1990	178	1990/04/26	68	6.8	0.04*g*		The peak acceleration is recorded at abutment.
				1994/08/14	5.7	3.2	0.017*g*		
				1994/10/10	60	5.3	0.005*g*		
Shapai [21]	China	2003	132	2008/05/12	36	8.0		−1.5	Slight damage
Techi [1]	Taiwan, China		181	1986/11/15			0.167*g*		
Fei-Tsui [4,5]	Taiwan, China	1987	122.5	1994/06/05	43	6.2	0.032*g*	−19	
				1999/09/21		7.3	0.136*g*	−23	
Pacoima [1,16]	USA	1928	113	1971/02/09	5	6.6	1.25*g*	−45	A section of upper left abutment rock slid, and the joint between the dam and thrust block opened almost 1 cm. The peak acceleration is recorded at a ridge on the left abutment about 15 m above the dam crest.
				1994/01/17	18	6.8	2.0*g*	−40	The upper left abutment rock slid again. The joint at the thrust block opened 5 cm at the crest. A few cracks were observed. The peak acceleration is obtained along the abutments near the crest.
				2001/01/13	6	4.3	0.16*g*	−41	No damage
Big Tujunga [1]	USA	1931	77	1971/02/09	32	6.6	0.25*g*	−29	No damage. The peak acceleration is recorded at abutment.
Santa Anita [1]	USA	1927	70	1971/02/09	27	6.6	0.17*g*		No damage The peak acceleration is recorded at right abutment.
Tonoyama [1,22]	Japan	1957	64.5	1960/12/26	75	6.0	0.03*g*		No damage
Nagawado [1,23]	Japan	1970	155	1984/09/14	37	6.8	0.247*g*	−24	
Ikehara [24]	Japan	1964	111	1995/01/17	106	7.2	0.082*g*		
Kurobe [1,22]	Japan	1963	186	1961/08/19	10	4.9	0.185*g*	−85	Concrete placement nearly complete. The peak acceleration is recorded at foundation rock.
				1972/09/08	8	3.9	0.116*g*		
Ambiesta [1,25]	Italy	1956	59	1976/05/06	22	6.5	0.33*g*		No damage. The peak acceleration is recorded at abutment.
Maina diSauris [25]	Italy	1952	136	1976/05/06	43	6.5			No damage
Barcis [25]	Italy	1955	50	1976/05/06	48	6.5			No damage
Talbacchia [1,26]	Italy	/	77	1986/11/25	250	5.5	0.13 cm/s	−25	No damage
Monteynard [25]	France	1962	155	1963/04/23	0	4.9			No damage
Kariba [25]	Zambia/ Zimbabwe	1956	128	1963/08/14–1963/ 11/08	0	6.1			Slight damage
				2010/08/31	45	5.5			No damage
Mauvoisin [12,14]	Switzerland	1957	250	1993/06/14	71	4.4	< 0.015*g*		
				1994/11/01	0		0.014*g*		
				1996/03/31	13	4.6	0.014*g*		
				1996/07/15	100	5.2			
Emosson [14]	Switzerland	1974	180	2001/02/23	10	3.6	0.07*g*		
Punt-dal-Gall [14]	Switzerland	1968	130	1999/12/29	12	4.9	0.08*g*		
Barossa [1,27]	Australia	1902	36	1954/03/01	45	5.5			Few cracks
Ceres [1,27]	South Africa	1950	30	1969/09/29	25	6.6			Few cracks and leakage
Rapel [1,27]	Chile	1968	112	1968/03/03		7.7	0.31*g*	0	Few cracks on the inner walls of the spillway intakes; minor damage on the power intakes.
Susqueda [27]	Spain	1968	135	1969/02/28		8.0			More seepage

[a] Generally it is the recorded peak acceleration at the dam crest.
[b] Water levels preceded by a minus are distances below the crest of the dam, i.e., a water level at −19 m is 19 m below the dam crest.