Engineering Failure Analysis 57 (2015) 188–201

Contents lists available at ScienceDirect

Engineering Failure Analysis

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

A field investigation into penetration cracks close to dam-to-pier interfaces and numerical analysis

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ARTICLE INFO

Article history:
Received 5 June 2015
Received in revised form 15 July 2015
Accepted 18 July 2015
Available online 23 July 2015

Keywords:
Cracks
Finite element analysis
Stress analysis
Stress concentrations
Stress distribution

ABSTRACT

This paper is a preliminary attempt to clarify a cracking issue confronting a double-curvature arch dam. The cracking occurs in the immediate vicinity of the interfaces between the dam body and some of its gate piers. This study seeks to address what is the biggest factor in the occurrence of the cracks. Both an on-site examination and a finite element analysis (FEA) were performed. The on-site examination consists of crack inspection and a concrete strength test. The FEA primarily focuses on structural loads (gravity and hydraulic thrust). The most obvious finding to emerge from the on-site examination is the symmetrical distributions of the cracks in the piers. The trends of the calculated stress contours correlate fairly well with those of the observed crack propagations, regardless of whether or not the hydraulic thrust is considered in the FEA. Our work has led us to conclude that the cracks result primarily from gravity rather than the hydraulic thrust. The cracking issue is independent of the water storage of the reservoir. Long-term and regular monitoring of the cracking lengths and openings should be a priority. The present findings have important implications for further reinforcement and maintenance work on the cracking gate piers.

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1. Introduction

Hydro projects are often equipped with water release systems, which release excess water from reservoirs. In order to control the amount of water released, water release systems have hydraulic floodgates, which are installed in gate chambers. Gate chambers can be built in channels for concrete dams to save space for arrangements of other hydraulic structures. In this case, the gate chamber penetrates the dam body and with the gate closed, the chamber can work together with the dam as a water retaining structure.

A gate chamber built in an arch dam in a general way partially hangs from the dam due to the arch dam's limited thickness. In such a case, the hanging portions of the gate chamber at the upstream and downstream sides are cantilever structures. The interfaces between the hanging portions and the dam are responsible for the load transfer. So the structural performance of the interfaces and their immediate vicinity is a vital factor affecting the operating condition of the in-dam water release system. Cracks at dam-chamber junctions, if they exist, might result in a failure of the system.

As regards cracking in concrete dams, it is a continuing concern within the field of dam engineering. In 1997, Graham reported a series of case histories from around the world on the care and rehabilitation of dams affected by serious cracking [1]. Extensive cracking was noticed in the Norfork Dam during its construction. This led to the first reported Civil Engineering application of the Finite Element Method (FEM), as far as we know [2,3]. In the 1960s, a total of 1289 cracks were observed at the faces of the Krasnoyarsk Dam although temperature-control measures had been taken during its construction [4]. Crack systems were detected on both the upstream and downstream faces of the Kölnbrein arch dam in the late 1970s and early 1980s, and they were investigated with

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http://dx.doi.org/10.1016/j.engfailanal.2015.07.031
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computer simulation and fracture mechanics by Ingraffea et al. [5–7]. Immediately at the initial operation stage of the Cabril Dam, a significant horizontal crack was detected on its downstream face. After a series of repair works, the dam cracked again in the same zone with the refilling of the reservoir [8]. Over the last decade, the Xiaowan arch dam has already become a milestone in China and even the world dam engineering development, a typical case for study on cracking in concrete dams [9]. In a word, to date there are still considerable uncertainty and unpredictability on cracking issues confronting concrete dams.

Turning now to arch dams, for many years they have been considered as monolithic concrete blocks in finite element analysis (FEA) and experimental investigations [10–13]. Existing research [14] recognizes the critical roles played by various joints in seismic responses of arch dams. Together these studies [10–14] provide important insights into the structural performance of monolithic concrete blocks of arch dams under various loads. One issue that needs to be raised is whether various cavities in arch dams, such as galleries and outlets, have significant effects on the structural performance of arch dams.

Some studies, for example [15] and [16], have been carried out on the aforementioned issue. To better understand the cause of crack formation in the upper gallery of an arch-gravity dam, Malla and Wieland carried out an FEA of the dam-foundation system [15]. They draw our attention to the zones of relatively high tensile stresses on the walls of the upper gallery where cracks were observed. They reach the conclusion that the observed crack on the downstream wall is of unstable nature and it is expected to eventually penetrate up to the downstream face of the dam. A recent study by Lin et al. involved two case studies on the outlet cracking at the Goupitan and Xiaowan arch dams in China [16]. In addition, they provided an in-depth comparative FEA of the Xiluodu arch dam with and without the in-dam outlets showing their significant effects on the structural performance of the dam. Overall, these studies [15,16] highlight the need for considering various cavities in the structural analysis of arch dams because in-dam cavities break the structural continuity of dam bodies.

The aim of this study has therefore been to clarify a cracking issue confronting a double-curvature arch dam. The cracking occurs in the immediate vicinity of the interfaces between the dam body and the gate piers of the lower in-dam outlets, where structural discontinuity exists. The central question in this study asks what is the biggest factor in the occurrence of the cracks. Both an on-site examination and an FEA were performed in this investigation. The study provides the basis for further reinforcement and maintenance work on the cracking gate piers.

This paper is organized as follows. In Section 2, a brief overview of the dam and an on-site examination are presented. We perform a numerical analysis of the cracking gate piers in Section 3. Causes of the cracks are discussed in Section 4. Some suggestions for further reinforcement and maintenance work are also offered in Section 4. Our conclusions are drawn in the final section.

2. On-site examination

2.1. Brief introduction to the dam

The double-curvature arch dam completed in 2005 is located in Hubei province, China. It has a maximum height of 84.8 m and a crest length of 191.8 m. The crest width is 5 m and the maximum base width is 16 m. The dam consists of eleven monoliths and has five in-dam outlets at two different elevations. The three upper outlets are in the No. 5, No. 6 and No. 7 monoliths, while the two lower outlets are in the No. 4 and No. 8 monoliths. The developed view and the real-world scene of the downstream face of the dam are presented in Fig. 1.

2.2. Structural features of the lower outlets

The lower outlets are 6.2 m wide and 6.5 m high. Each of the lower outlets has a gate chamber equipped with a bulkhead gate and a tainter gate. The gate chambers partially hang from the dam upstream and downstream, with overhanging lengths of 10.2 m and 16.182 m, respectively. The downstream cantilever portions of the gate chambers are 13.2 m wide and supported by continuous brackets. Each bracket has a slope ratio of 1.3:1 or 1:1 on either side (3.5 m wide for each side) and that of 0.8:1 in the middle (6.2 m wide). Fig. 2 details the structural data on the downstream cantilever portion of the right gate chamber and its bracket support.

2.3. Crack inspection

In an attempt to clarify the cracking issue, we performed crack inspection of the downstream cantilever portions of both gate chambers for the lower outlets in December, 2013. Penetration cracks were observed in all the four gate piers. For brevity, hereafter LL-P and RL-P will be used to refer to the Left and Right piers (on the downstream side) of the gate chamber for the Left lower outlet, respectively. LR-P and RR-P will be used, similarly, to refer to those piers for the Right lower outlet. Fig. 3 shows the observed penetration cracks in the gate piers. Table 1 lists the cracking lengths and openings.

It is apparent from Fig. 3 that the cracks penetrate the piers and propagate downwards and upstream from the top surfaces of the piers into the dam body. The single most striking observation to emerge from the comparison in Fig. 3 and Table 1 is that the cracks in the left and right piers of each gate chamber are in the main symmetrical. The symmetry allows us to put forward a hypothesis that (1) gravity (G), or (2) the combination of gravity and hydraulic thrust transferred through the tainter gates (G + HT), gives rise to the cracks in the piers. We suggest this hypothesis as a possible explanation for the cracks since both gravity and the hydraulic thrust should bring about horizontal tensile stresses in the piers. It seems likely that the horizontal tensile stresses produce the cracks in consideration of the weak tensile capacity of concrete material.

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