MONITORING AND DEFORMATION ASPECTS OF LARGE CONCRETE FACE ROCKFILL DAMS

Anna SZOSTAK_CHRZANOWSKI[1], Nianwu DENG[1,3], and Michel MASSIÉRA[2]

[1]*Canadian Centre for Geodetic Engineering, University of New Brunswick, Canada*
[2]*Faculté d'ingénierie (génie civil), Université de Moncton, Canada*
[3]*State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, China*

Abstract: Concrete face rockfill dams (CFRDs) are gaining a worldwide recognition as the most economical type of dams to be constructed in extreme northern and sub-Antarctic regions. Height of CFRDs may exceed 200 m. Safety of CFRDs depends on the proper design, construction, and monitoring of actual behaviour during the construction and during the operation of the structure. The main concern for the safety of CFRDs is the deformation of the concrete face. During the reservoir filling, the load of the water and deformations of the dam rockfill, force upstream concrete slab to deform. The displacements of the concrete face during the reservoir filling should not exceed the maximum allowed values in order to maintain the structural integrity of the concrete face. In a classic CFRD where the concrete face is constructed after the end of construction of the rockfill embankment, it is very important to estimate the displacements of the concrete face during the filling of the reservoir and to verify if these displacements are lower than displacements compatible with the structural integrity of the concrete face. Due to the uncertainty of the model parameters, careful monitoring of the dam and its surroundings are required in order to verify and enhance the model. The paper presents a study of behaviour of the Shibuya Dam in P. R. China, the tallest (233 m) concrete face rockfill dam in the world using results of monitoring and FEM analysis. The study shows that the in real time fusion of the monitoring results and FEM analysis would give indication that the deformations of the concrete face reached critical values before the reservoir level reached the maximum level. This information could trigger the proper action from engineering team and lead to prevention of the cracking of the concrete face.

1. INTRODUCTION

Concrete face rockfill dams (CFRDs) are gaining a worldwide recognition as the most economical type of dams to be constructed in extreme northern and sub-Antarctic regions. Height of CFRDs may exceed 200 m. Use of not sensitive to the frost action type of rockfill and construction technology allows lengthening the construction season. The total duration of the construction of CFRDs with regard to the total duration of construction of earth dams is on average reduced by one year. The reduced construction time reduces largely the costs of construction and makes hydroelectric projects more economic. Cooke (1984) indicated that the use of this type of dams seems inevitable in the regions of the world which have extreme climates.

Most of the constructed CFRDs rest on the bedrock. However, there are some CFRDs constructed on soil foundations. Examples are: Potrerillos dam, 116 m of height, Pichi-Picun Leufu dam, 54 m of height, and Los Caracoles dam, all in Argentina (Pujol, 1999); Santa Juana dam, 103 m of height (Astete and al., 1992), and Puclaro dam, 83 m of height in Chile (Noguera and al.1999); West Seti dam, 190 m of height in Nepal (Kenneally and al., 2001) and Morro de Arica dam, 215 m of height, in Peru. The thickness of alluvium deposits of the foundation of CFRDs do not generally exceed 70 m with the exception of Puclero's dam (Noguera and al., 1999) which rests on alluvium deposits of 113 m thick.

China has built more than 170 CFRDs. More than 40 CFRDs have height larger than 100 m. Examples are: Shuibuya 233 m of height, Jiangpinghe 221 m of height, Sanbanxi 186 m of height, Hongjiadu 179.5 m of height, Tianshengqiao I 178 m of height, and Tankeng 162 m of height. Some of them developed cracks in their face slabs.

The main concern for the safety of CFRDs is the deformation of the concrete face. During the reservoir filling, the load of water and deformations of the dam rockfill force concrete slab to deform. The concrete slab acts as an impervious membrane and any development of cracks in the slab would allow for water to penetrate the rockfill of the dam and cause the structure to weaken or even loose stability. According to the working state, force distribution and hydraulic features of CFRD, proper zoning on dam filling materials is carried out to take full utilization of the material from structure excavation and to reduce the investment under the condition that the safety of operation is ensured.

During the construction of a rockfill dam, internal deformations take place due to change in effective stresses and due to creep and secondary time effects. During the first filling of the reservoir, considerable movements can develop in the dam and in the concrete face. Thereafter, the rate of movement generally diminishes with time, except for variations associated with periodic raising and lowering of the reservoir and as a result of earthquakes or tectonic plate movements. In a classic CFRD where the concrete face is constructed after the end of construction of the rockfill embankment, it is very important to estimate the displacements of the concrete face during the filling of the reservoir and to verify if these displacements are lower than displacements compatible with the structural integrity of the concrete face.

Safety is the most important reason for observing the deformations of dams. Too large or unexpected deformations can be the only indication of potential problems of the dam or its foundation. Another reason for observing the deformations of dams, of less immediate concern but of potentially great long-range significance to engineering profession, is the need for better understanding of basic design concepts, stress-deformation characteristics, and geotechnical characteristics of soil and rockfill. The development of prediction methods, which allow a determination of deformations and stress distribution and comparison of predicted values with observed, constitutes very valid tools to control safety.

This paper describes the potential benefits of using monitoring results in verification of the design behaviour of the CFRD dam during filling up a reservoir. The study shows that the in real time fusion of the monitoring results and FEM analysis would give indication that the deformations of the concrete face reached critical values before the reservoir level would reach the maximum level. This information could trigger the proper action from engineering team and lead to prevention of the cracking of the concrete face. The inreal-time detection and evaluation of differences between monitoring results and results obtained from a prediction analysis could result in a redesign of the dam concrete slab and prevent the cracking of the concrete face. The methodology is illustrated using Shuibuya CFRD example.

2. SHUIBUYA DAM

2.1 Parameters of Shuibuya CFRD

Shuibuya CFRD is presently the highest of its kind in the world. It is 233 m high and 608 m long (Fig. 1). The crest width is 12m with a 5.2m high "L" shape parapet at the crest. The upstream dam slope ratio is 1:1.4 and the downstream slope ratio is 1:1.25. The concrete slab is 0.3 m thick at the top and 1.1m thick at the bottom. The slab area is 127 000 m^2 and the maximum inclined slab is 392 m long. The slab is divided into three construction stages with two construction joints at elevation 280 m and 360 m.

The main and secondary rockfill zone of Shuibuya CFRD used the Maokou formation limestone and the mix of soft and hard limestone of Qixia formation. The dam zoning is shown in Fig. 2. The geotechnical parameters of the rockfill are given in Table 1 (Guo et al., (2004).

The dam construction encountered certain difficulties (file://E:\LecturesCM\Shuibuya Water Conservancy Project.htm). At a design stage the finite element analysis was performed by Shuibuya Water Conservancy Project. In the analysis the rockfill was modeled using hyperbolic model with geotechnical parameters shown in Table 1. The predicted maximum deformation of the concrete face was 0.60 m at about one third of the dam height (file://E:\LecturesCM\Shuibuya Water Conservancy Project.htm).

The FEM analysis was also performed by Guo et al., (2004). The predicted maximum displacement of concrete face was calculated and reached value 0.653 m.

Compared with earlier completed projects, the slab deflection of Hongjiadu is 0.45 m, Tianshengqiao is 0.70 m, versus the designed 0.60 m at Shuibuya dam. The design deformation of the slab of Shuibuya dam can be evaluated as being too small in relation to its 233 m height and 403 m length of the concrete slab.

(http://www.biztrans.cn/CN/Samplefiles/SbyKeytech.htm).

Figure 1 - Shibuya dam.

Zone	γ [kN/m^3]	$\Delta\phi o$	$\Delta\ \phi$	K	n	R_f	K_{ur}	K_b	m
Cushion	21	56	10.5	1200	0.45	0.78	2400	750	0.20
Transition	21	54	8.6	1000	0.40	0.85	2000	450	0.15
Main Rockfill	21	52	8.5	1100	0.35	0.82	2200	600	0.10
Secondary Rockfill	21	50	8.4	850	0.25	0.80	1700	400	0.05
Downstream Rockfill	21	52	8.5	1100	0.35	0.82	2200	600	0.10

Table 1 - Design Geotechnical Parameters Shuibuya CFRD.

During filling up the reservoir cracks in the concrete face started developing. The cracks started developing at the 1st stage of the face slab. Total 255 cracks developed and they were observed before the water level in the reservoir reached 200m. The general characteristics of cracks are as follow: 195 cracks have width < 0.1 mm; 54 cracks have 0.1 mm ≤ crack width < 0.03 mm, and 6 cracks have width ≥ 0.3 mm (file://E:\LecturesCM\Shuibuya Water Conservancy Project.htm). The development of the cracks of the concrete slab indicated that the actual deformations of the slab were larger than predicted and exceeded the maximum allowed deformations. The deformation field of the concrete slab was following the deformation field of rockfill of the dam. Most likely one of the reasons for the larger deformations of the rockfill was that the in-situ values of geotechnical parameters were different than those assumed during design of the dam.

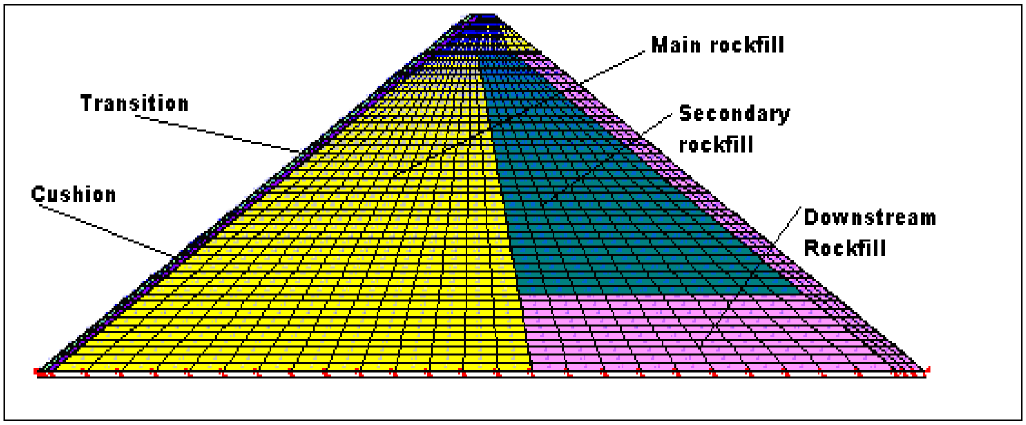

Figure 2 - Shibuya Dam, FEM mesh and dam zoning.

2.2 Monitoring of Shuibuya CFRD

The geotechnical monitoring using interior wire extensometers to monitor interior displacement of the points located in the rockfill was started at the beginning of the filling up of the reservoir. The interior wire extensometer is shown on Fig. 3. The location of the monitored points is shown in Fig. 4. The measured settlements of point 25, point 29, and point 32 during the filling up the reservoir are given in Fig. 5, Fig. 6, and Fig.7 respectively.

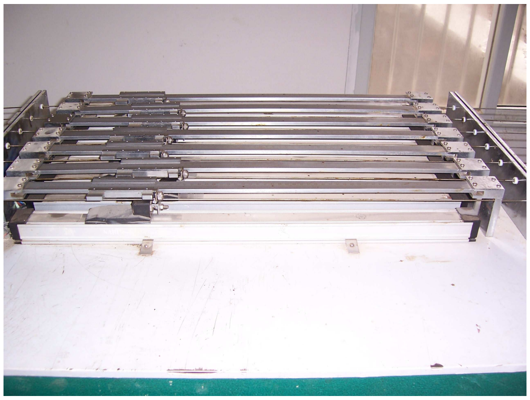

Figure 3 - Interior wire extensometer.

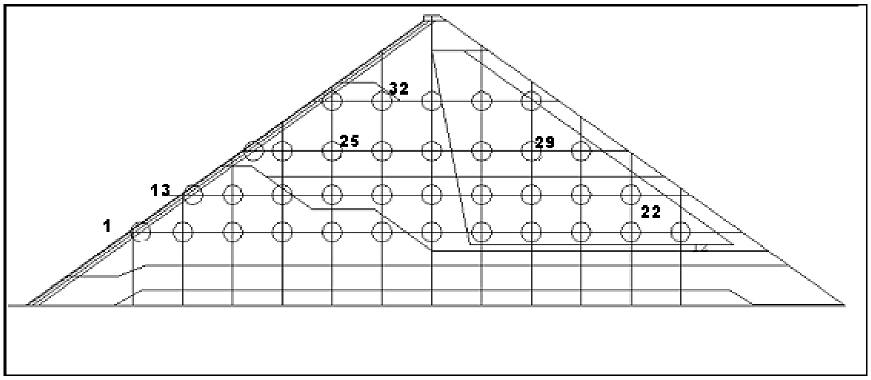

Figure 4 - Location of the monitored points.

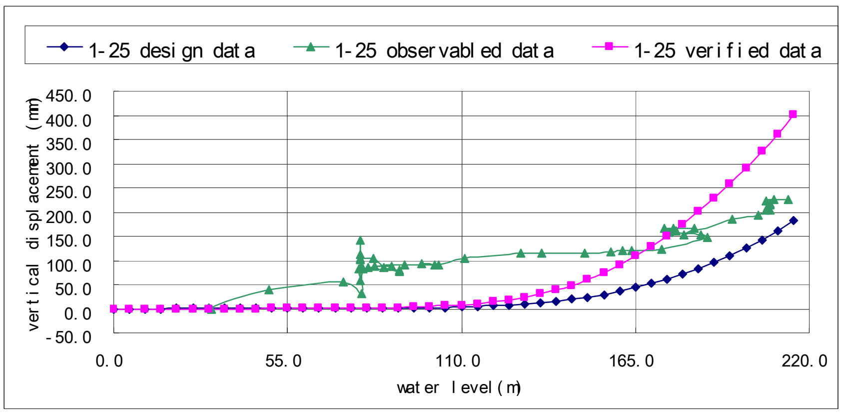

Figure 5 - Settlement of pt 25.

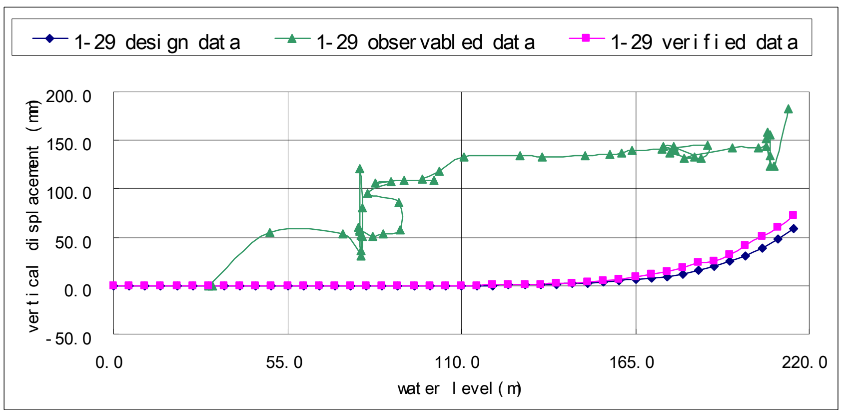

Figure 6 - Settlement of pt 29.

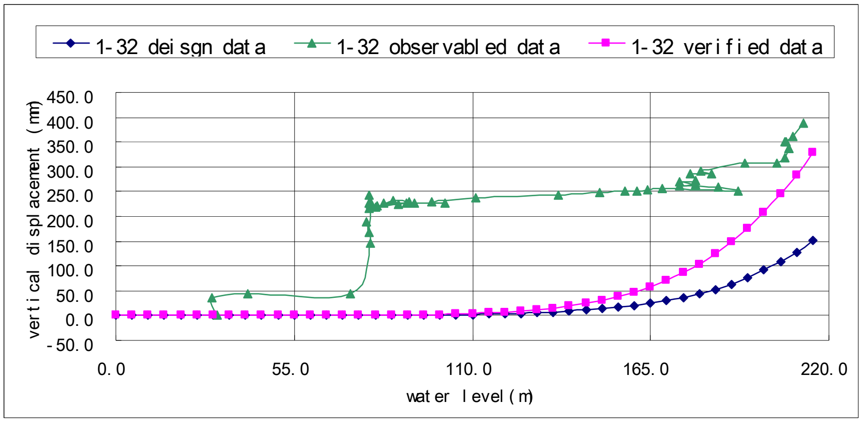

Figure 7 - Settlement of pt 32.

3. FEM ANLYSIS OF SHUIBUYA DAM

The goal of the presented research was to explain the development of cracks in the concrete face of Shuibuya dam during filing up the reservoir. The research was divided into two stages. First stage of the research was the reproduction of the FEM results obtained by Guo et al., (2004) using the values of geotechnical parameters defined at the design stage of the dam and given in Table 1. The second stage of the research was the FEM analysis using a new set of geotechnical parameters, which values were calibrated using the monitoring results. The FEM analyses were performed using hyperbolic model of the behaviour of the rockfill (Duncan and Chang, 1970). The FEM analysis was performed using SIGMA/W software (Krahn, 2004). The FEM model is shown in Fig. 2.

The first FEM analysis using the design geotechnical parameters gave the maximum value of the deformation of the concrete slab equal to 0.50 m. The calculated displacement is shown in Fig. 8. The result is in good agreement with the maximum values obtained by Guo et al., (2004) and Water Conservancy Project. The settlements of point 25, point 29, and point 32 were compared with the measured settlements. The calculated settlements were significantly smaller than measured (Fig.5, Fig. 6, and Fig.7). It indicated that the geotechnical parameters used in the prediction analysis did not agree with in-situ values.

The second FEM analysis was performed using calibrated geotechnical parameters of the rockfill. The parameters were based on parameters values of rockfill of Toulnustouc dam build in Canada (Massiera et al., 2005). The geotechnical parameters are given in Table 2. The maximum deformation of the concrete face at the end of filling of reservoir is 1.18 m (Fig. 4). The calculated settlements of point 25, point 29, and point 32 were larger than calculated at the design stage (Fig. 5, Fig 6, and Fig 7). The calculated deformations were closer to the measured values.

In Fig. 8 the distribution of settlements of the concrete face using verified values of geotechnical parameters for different heights of water in reservoir are shown. On the same Fig. 8, the maximum settlement for the maximum water level using design geotechnical parameters, is shown. In the figure 8 it is shown that when the level of water in the reservoir reached 150 m, than the maximum displacement of the dam modeled with verified geotechnical parameters was larger than maximum predicted displacement.

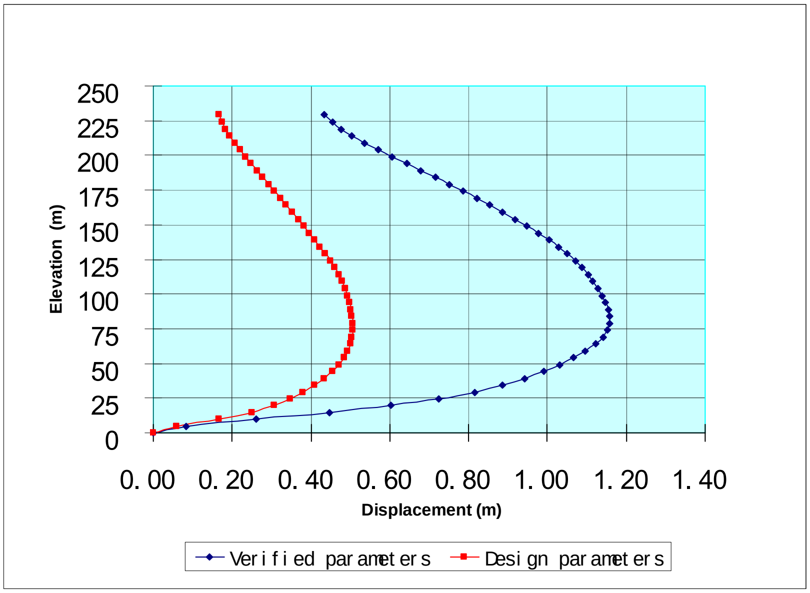

Figure 8 - Calculated settlements (m) at the end of the filling of the reservoir for a CFRD

Zone	γ [kN/m^3]	$\Delta\phi o$	$\Delta\ \phi$	K	n	R_f	K_{ur}	K_b	m
Cushion	21	45	8.6	1000	0.5	0.8	1200	800	0.2
Transition	21	45	8.6	1000	0.5	0.8	1200	800	0.2
Main Rockfill	21	45	8.5	500	0.5	0.8	600	240	0.2
Secondary Rockfill	21	45	8.4	400	0.5	0.8	480	240	0.2
Downstream Rockfill	21	45	8.4	400	0.5	0.8	480	240	0.2

Table 2 - Verified Geotechnical parameters

4. CONCLUSIONS

The study shows that the in real time fusion of the monitoring results and FEM analysis would generate information that the deformations of the concrete face reached critical values before the reservoir level reached the maximum level. The fusion process of the monitoring results and FEM analysis should work in real time using data sets for measurements results and FEM results interconnected using specific correlation criteria. The result of real time fusion would trigger the proper action from engineering team what would lead to prevention of the cracking of the concrete face.

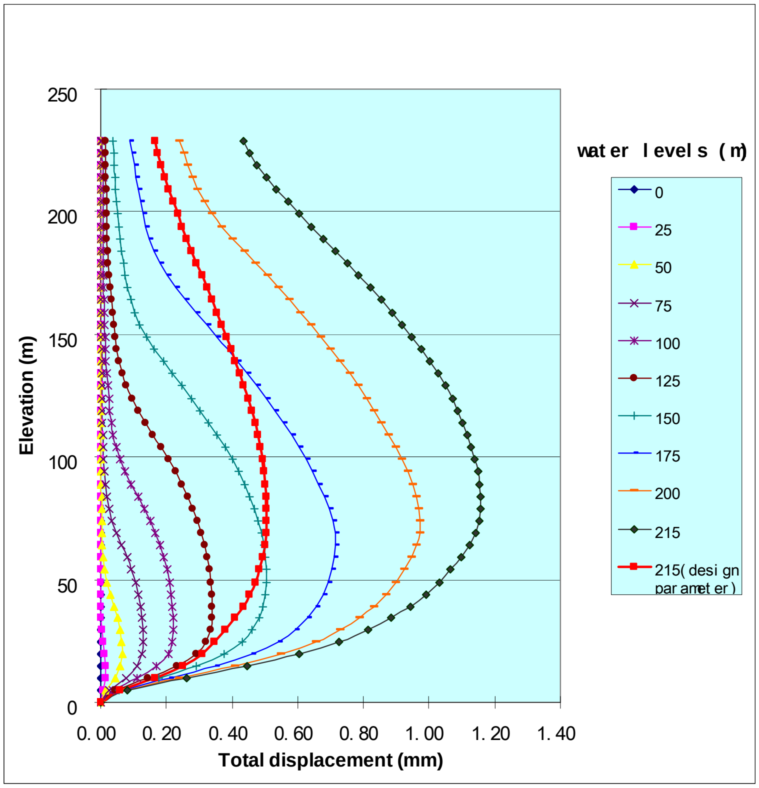

Figure 9 - Total displacements (m) of the concrete face slab during the filling of the reservoir

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Key Technical Issues of Shuibuya CFRD http://www.biztrans.cn/CN/Samplefiles/SbyKeytech.htm

Corresponding author contacts

Anna SZOSTAK-CHRZANOWSKI
amc@unb.ca
Canadian Centre for Geodetic Engineering, University of New Brunswick
Canada